# NAVAL POSTGRADUATE SCHOOL
# Monterey, California

# THESIS

**EVALUATION OF COMBAT SERVICE SUPPORT LOGISTICS CONCEPTS FOR SUPPLYING A USMC REGIMENTAL TASK FORCE**

by

Thomas A. Lenhardt

September 2001


| | |
|---|---|
| Thesis Advisor: | Arnold H. Buss |
| Co-Advisor: | Gordon H. Bradley |
| Second Reader: | Javier Salmeron |

# Report Documentation Page

| Report Date | Report Type | Dates Covered (from... to) |
|---|---|---|
| 30 Sep 2001 | N/A | - |

| | |
|---|---|
| **Title and Subtitle**<br>Evaluation of Combat Service upport Logistics Concepts for Supplying a USMC Regimental Task Force | **Contract Number** |
| | **Grant Number** |
| | **Program Element Number** |
| **Author(s)**<br>Lenhardt, Thomas A. | **Project Number** |
| | **Task Number** |
| | **Work Unit Number** |
| **Performing Organization Name(s) and Address(es)**<br>Research Office Naval Postgraduate School Monterey, Ca 93943-5138 | **Performing Organization Report Number** |
| **Sponsoring/Monitoring Agency Name(s) and Address(es)** | **Sponsor/Monitor's Acronym(s)** |
| | **Sponsor/Monitor's Report Number(s)** |
| **Distribution/Availability Statement**<br>Approved for public release, distribution unlimited | |
| **Supplementary Notes** | |
| **Abstract** | |
| **Subject Terms** | |
| **Report Classification**<br>unclassified | **Classification of this page**<br>unclassified |
| **Classification of Abstract**<br>unclassified | **Limitation of Abstract**<br>UU |
| **Number of Pages**<br>122 | |

THIS PAGE INTENTIONALLY LEFT BLANK

# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



**1. AGENCY USE ONLY *(Leave blank)***

**2. REPORT DATE**
September 2001

**3. REPORT TYPE AND DATES COVERED**
Master's Thesis

**4. TITLE AND SUBTITLE**
Evaluation of Combat Service Support Logistics Concepts for Supplying a USMC Regimental Task Force

**5. FUNDING NUMBERS**

**6. AUTHOR(S)**
Lenhardt, Thomas A.

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
Naval Postgraduate School
Monterey, CA 93943-5000

**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
Air Force Office of Scientific Research
801 North Randolph Street
Arlington, VA 22203-1977

**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**

**11. SUPPLEMENTARY NOTES**
The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. **DISTRIBUTION / AVAILABILITY STATEMENT**
Approved for public release; distribution is unlimited.

**12b. DISTRIBUTION CODE**

**13. ABSTRACT**

One of the primary responsibilities of a Marine Corps Combat Service Support Element (CSSE) is to provide water, fuel, and ammunition requirements for the primary task forces and other Marine Expeditionary Force (MEF) elements. This thesis evaluates existing and proposed concepts on how to best use the CSSE resources of a Force Service Support Group to transport supplies to Regimental Combat Teams over constrained networks with time constraints. A model was developed that optimizes the use of resources, assets, and network routes. The model first solves a capacitated vehicle routing problem, where a set of customers has to be served by a fleet of vehicles within a certain time. The stochastic aspects of the problem are modeled through the use of a discrete event simulation that uses the results of the optimization model. The optimization model goes beyond the traditional routing problem by accounting for special features such as vehicle capacity for each commodity and cargo incompatibility (e.g. fuel and ammunition). The model includes both optimization of routes and simulation of stochastic elements. As a result, this thesis establishes a basis for future studies involved with modeling new concepts in Combat Service Support.

**14. SUBJECT TERMS**
Combat Service Support, Expeditionary Maneuver Warfare (EMW), Java, Logistics, Logistics Models, Mathematical Programming, Movement Control and Coordination, Optimization, Simulation, Transportation, Vehicle Routing Problem

**15. NUMBER OF PAGES**
122

**16. PRICE CODE**

| **17. SECURITY CLASSIFICATION OF REPORT** | **18. SECURITY CLASSIFICATION OF THIS PAGE** | **19. SECURITY CLASSIFICATION OF ABSTRACT** | **20. LIMITATION OF ABSTRACT** |
|---|---|---|---|
| Unclassified | Unclassified | Unclassified | UL |

**NSN7540-01-280-5500** **Standard Form298 (Rev. 2-89)**
**Prescribed by ANSI Std. 239-18**

THIS PAGE INTENTIONALLY LEFT BLANK

**Approved for public release; distribution is unlimited.**

# EVALUATION OF COMBAT SERVICE SUPPORT LOGISTICS CONCEPTS FOR SUPPLYING A USMC REGIMENTAL TASK FORCE

Thomas Anthony Lenhardt
Captain, United States Marine Corps
B.S., United States Naval Academy, 1994

Submitted in partial fulfillment of the
requirements for the degree of

**MASTER OF SCIENCE IN OPERATIONS RESEARCH**

from the

**NAVAL POSTGRADUATE SCHOOL**
**September 2001**

Author: Thomas A. Lenhardt

Thomas A. Lenhardt

Approved by:

Arnold H. Buss, Thesis Advisor

Gordon H. Bradley, Co-Advisor

Javier Salmeron, Second Reader

James N. Eagle, Chairman
Department of Operations Research

THIS PAGE INTENTIONALLY LEFT BLANK

## ABSTRACT

One of the primary responsibilities of a Marine Corps Combat Service Support Element (CSSE) is to provide water, fuel, and ammunition requirements for the primary task forces and other Marine Expeditionary Force (MEF) elements. This thesis evaluates existing and proposed concepts on how to best use the CSSE resources of a Force Service Support Group to transport supplies to Regimental Combat Teams over constrained networks with time constraints. A model was developed that optimizes the use of resources, assets, and network routes. The model first solves a capacitated vehicle routing problem, where a set of customers has to be served by a fleet of vehicles within a certain time. The stochastic aspects of the problem are modeled through the use of a discrete event simulation that uses the results of the optimization model. The optimization model goes beyond the traditional routing problem by accounting for special features such as vehicle capacity for each commodity and cargo incompatibility (e.g. fuel and ammunition). The model includes both optimization of routes and simulation of stochastic elements. As a result, this thesis establishes a basis for future studies involved with modeling new concepts in Combat Service Support.

THIS PAGE INTENTIONALLY LEFT BLANK

## DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the planner.

THIS PAGE INTENTIONALLY LEFT BLANK

**TABLE OF CONTENTS**

## LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

## EXECUTIVE SUMMARY


Distribution concepts developed to support the conflict mold of WW II and of the Cold War are now inadequate and require the development of a number of improvements. The Marine Corps' historical doctrine of redundant, multi-layered support have little place in light of changing strategic requirements. Force efficiency is improved by reducing the cost and "footprint" of distribution support and infrastructure.

U.S. national and military strategies are changing dramatically in response to massive global political and economic turbulence. This fundamental change calls for the U.S. to have flexible forces that can rapidly deploy. Further, the change in the international political situation and shift toward domestic priorities means that the defense establishment will have to manage its assets more efficiently and effectively. This combination of factors leads to studies on how to optimize the use of assets in the Combat Service Support environment and reduce the metal mountain of supplies currently employed in this environment. A system is needed that is more versatile, deployable, and expandable.

One of the primary responsibilities of a Marine Corps Combat Service Support Element (CSSE) in a wartime scenario is to provide water, fuel, and ammunition requirements for the primary task forces and other Marine Expeditionary Force (MEF) elements, such as Regimental Combat Teams. In addition to traditional "movement control and coordination" procedures, a decision model is needed that optimizes the use of resources and assets, network routes, vehicle and route capacity, and that provides daily load planning and management support to movement coordinators. "Load planning" refers to matching transportation assets/drivers with loads (supplies) and warfighting customers.

Operational planning is accomplished every 24 to 48 hours, whereas dispatching is done as often as possible. The output from operational planning is used to make dispatching decisions. A dispatcher must continuously make decisions on how much to load and where to send that materiel. This thesis models a distribution system and gives an operational perspective of the schemes of maneuver for the Combat Service Support

Detachment (CSSD) to utilize. The model first solves a capacitated vehicle routing problem, where a set of customers has to be served by a fleet of vehicles within a certain time. The stochastic aspects of the problem are modeled through the use of a discrete event simulation that uses the results of the optimization model. The optimization model goes beyond the traditional routing problem by accounting for special features such as vehicle capacity for each commodity and cargo incompatibility (e.g. fuel and ammunition). The model includes both optimization of routes and simulation of stochastic elements.

This thesis develops and presents a tactical transportation distribution model based upon a new theory of coordinating operational planning. Under the current doctrine, truckloads of supplies go back and forth between the parent Direct Support Combat Service Support Detachment (DS CSSD) and the Mobile Combat Service Support Detachment (MCSSD) to be ultimately delivered by the MCSSD to the supported Regimental Task Force (RTF) that needs to be replenished. A possible alternative would be for one large convoy to make a giant circuit between each of the RTFs as situational assessments permit. In other words, this alternative is a trial of the shift from the current General Support / Direct Support (GS/DS) task organization to more emphasis on GS. This change is projected to give the CSSE commander more command and control and a better ability to optimize the resources that are available.

The final product of the thesis is an analysis of what is gained by the new structure. The underlying objective of the model is to maximize the ability to meet delivery windows, which in turn typically maximizes the utilization of transportation assets or minimizes the number of empty trucks, known as deadheading. Further analysis of the simulation reveals whether units can be sustained under the new doctrine.

Based upon the output of the Vehicle Routing Problem and the simulation, the concept modeled shows that in similar scenarios a CSSE would be able to provide a majority of the requisition needs in an efficient manner when tasked with supporting a MEB. If 100% support is required then this model spells out the need for incorporating aircraft into the scenario, supplying more vehicles to the CSSE, or providing some other transportation asset to the CSSE for logistical use. However, if the CSSE were tasked

with supporting a smaller sized force such as a Task Force then additional assets would not be required. A CSSE with a similar structure and organization as the one modeled would have the capability to provide support needed with the vehicular assets that are available for its use.

Generally, the results show that when given exact time windows in which support needs to be provided, of the factors analyzed in this thesis the vehicular speed factor has the most significant effect on making a time window. The time to load, the total delays in loading, as well as delays along a designated route to provide support are not statistically significant when they are compared to the speed of the vehicle.

The result of this thesis is a first crucial step in what should be a dedicated analysis of the Logistics Operations Command and Control Capability (LOCCC) concept as developed by Colonel Grelson, 1st BSSG Commanding Officer. This thesis is a breakthrough study in the sense that in addition to time windows requirements in the vehicle routing problem, our model has special features such as vehicle capacity for each commodity and cargo incompatibility (e.g. fuel and ammunition) which has not been accomplished before in this field of study.

THIS PAGE INTENTIONALLY LEFT BLANK

## ACKNOWLEDGMENT

Throughout the course of this thesis I have met and worked with many professional people; I am grateful for their countless hours of dedicated help. Professor Arnold Buss, the learning curve has been tremendous. Professor Gordon Bradley, thank you for always having your door open. Professor Javier Salmeron, your dedication is beyond reproach. All three have been wonderful and I thank them for all of their assistance.

To my daughter, Grace: Daddy will finally have time to play with you again. I thank my wife, Jacqueline, most of all. This has been a long and arduous process. I thank you for the many 'all-nighters', for being my 'editor-in-chief', and for always sticking by my side. Your love and dedication are insurmountable and for that I am eternally grateful. I love you dearly and thank you for being so understanding of all the long hours this has taken. These past few years have been very demanding.

THIS PAGE INTENTIONALLY LEFT BLANK

# I. INTRODUCTION

*The employment of military forces and combat power decides the outcome of campaigns and operations. The success of these forces often depends on sound, timely deployment and support. A well-defined, integrated transportation system is a critical part of this support. Joint Pub 4-01.3*

This thesis evaluates existing and proposed concepts on how to best use the Combat Service Support Detachment (CSSD) resources of a Force Service Support Group (FSSG) to get supplies to the demand centers (Regimental Combat Teams) over constrained networks with time constraints. The traditional support network has one General Support CSSD (GS CSSD) and a Direct Support CSSD (DS CSSD) that supports its Mobile-CSSD's (MCSSD's) (refer to Figure 1). Under the present doctrine of always keeping DS MCSSDs, convoys of supplies cycle between the parent Direct Support Combat Service Support Detachment (DS CSSD) and the MCSSD to be ultimately delivered by the MCSSD to the supported Regimental Task Force (RTF) that needs to be replenished. Is that the best use of resources? Should trucks from the MCSSDs continue to serve in Direct Support of a Regimental Task Force under all circumstances as doctrine currently has them operate or should support shift, as METT-TSL permits, to place more emphasis on keeping MCSSDs in General Support? This proposed shift in doctrine is a radical change in the way a Combat Service Support Detachment operates. The shift suggests the breaking of old paradigms and the placement of more emphasis on General Support. More emphasis on GS will give the Commanders of the CSSDs more control of transportation assets that are utilized to provide support. The new doctrine would allow vehicles to be routed as needed whether it is in one large convoy making a circuit between each of the RTFs supported as the situation permits or it is a few vehicles being routed to meet high priority demands. Does this shift in the paradigm give the commander a better ability to optimize resources that are available? What is gained by the different structures that are modeled?

The CSS environment is characterized by time to make deliveries, uncertainty of demand, and operational tempo. Planners must follow the events on the battlefield and anticipate requirements before they are requested or called for. Hence, there is a fine balance between pushing sustainment forward and waiting for request "pull" logistics.

The job of routing vehicles is currently not done efficiently. Efficient transportation not only involves effective organization and control procedures, but it also involves movement and resource management (Joint Pub 4-01.3 1996). Basically the DS Combat Service Support Element (DS CSSE) delegates responsibility and lets the MCSSD's execute delivery. The Command and Control (C2) is decentralized down to a Gunnery Sergeant in Motor Transportation in charge of Operations at the MCSSD (Gannon Oct 2000).

By evaluating concepts on how to best use the resources of a CSSD, the model developed here conducts the crucial initial step in the development of any new doctrine, which is a proper analysis. The proper analysis in this case consisted of breaking down a concept of Combat Service Support to its roots, performing a simulation of the same, and conducting an exploratory analysis of that simulation.

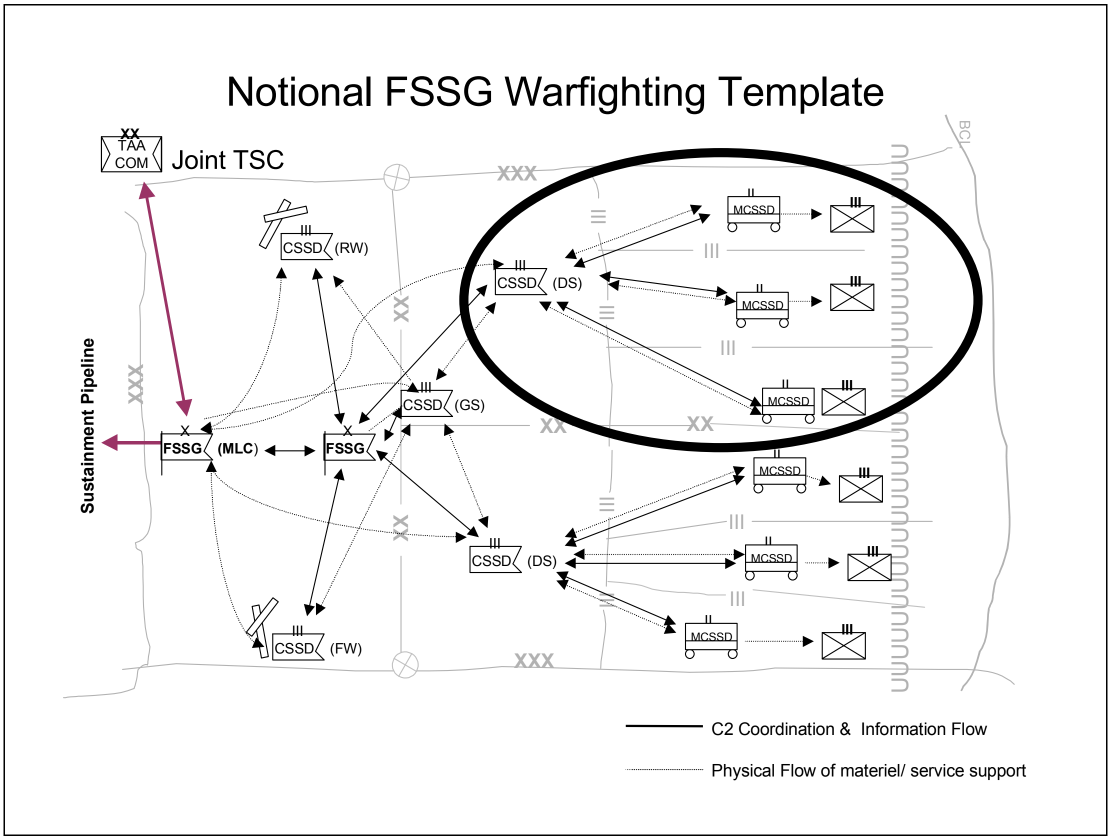


***Figure 1. Notional FSSG Warfighting Template (From: Gannon Nov 2000)***

*This figure depicts a conceptual layout of the current command and control battle organization of the FSSG. It is implied by the diagram that the reinforced FSSG is sourced from multiple FSSGs. The bold circled area indicates the scope of the current CSS organization that is reviewed in this thesis.*

THIS PAGE INTENTIONALLY LEFT BLANK

# II. BACKGROUND

The purpose of this chapter is to provide the reader with an overview of the organizational structure and operational concepts modeled in this thesis.

## A. FORCE SERVICE SUPPORT GROUP (FSSG)

As documented in Marine Corps Warfighting Publication 4-11 (MCWP 4-11), the FSSG is the primary logistics organization in the Fleet Marine Force (FMF). Its mission is to provide sustained Combat Service Support (CSS) throughout the Marine Forces / Marine Expeditionary Forces (MARFOR/MEF) AOR (Gannon Feb 2001). It is designed to support one Marine Division (MarDiv) and one Marine Aircraft Wing (MAW) when in garrison, separately deployed, or deployed as a Marine Air Ground Task Force (MAGTF). The FSSG deploys in its entirety when the entire MEF deploys.

CSSE's are drawn from the FSSG and are task organized to provide a range of support functions which span the six functional areas of CSS: supply, maintenance, transportation, deliberate engineering, services, and health services. This thesis deals with a small portion of the functional areas of supply and transportation.

## B. COMBAT SERVICE SUPPORT DETACHMENT (CSSD)

A CSSD is task organized from a variety of sources. It may or may not be part of a MAGTF, depending on the situation/mission. "The ability to tailor a CSSE to specific needs is one of the greater strengths of an FSSG"(O'Donovan 1991). For example, a CSSD might augment a battalion landing team (BLT) conducting independent operations or support a squadron located at a remote airfield. The FSSG normally provides the command and control element of the CSSD. The numeric designation of a CSSD is as follows (MCWP 4-11 2000):

1st FSSG: 11-19
2nd FSSG: 21-29
3rd FSSG: 31-39
4th FSSG: 41-49

## 1. Direct Support (DS)

Each CSS unit assigned the mission of direct support is immediately responsive to the needs of the designated supported unit. It furnishes sustained support to that element and coordinates its operations to complement the concept of operations of the supported element. The essence of the direct support mission is the one-to-one relationship between supporting and supported units. The direct support mission is the most decentralized of the formal missions. A CSS unit assigned the DS mission (MCWP 4-11 2000):

**a)** *Responds to requests for support, in order of priority, from its supported unit first, then from those of its higher CSS headquarters, and finally those from its subordinate unit. In the event of conflicting requests, support to the supported unit takes precedence.*

**b)** *Has as its area of responsibility (AOR) the supported unit's area of operations (AOA).*

**c)** *Establishes liaison with the supported unit.*

**d)** *Establishes communication with the supported unit and higher CSS headquarters.*

**e)** *Is positioned by higher CSS headquarters. This complements the overall CSS mission and considers the needs of the supported unit. In the event there is no higher CSS headquarters, it positions itself.*

**f)** *Has operations planned by higher CSS headquarters in coordination with the supported unit.*

## 2. General Support (GS)

A mission of GS provides CSS for the force as a whole, or designated component thereof, under the direction of the CSS headquarters. This mission provides responsive support to the requirements of the supported commander. However, the CSSE commander retains control of the prioritization of tasks. The GS mission is the most centralized tactical mission. A unit assigned this mission (MCWP 4-11 2000):

**a)** *Responds to CSS requests, in priority, from: higher CSS headquarters, supported unit, and its subordinate unit.*

**b)** *Has as its AOR the AOA of the supported unit.*

**c)** *Establishes liaison as required by the operational situation with the subordinate unit.*

**d)** *Establishes communication with the supported unit and higher CSS headquarters.*

**e)** *Is positioned by higher CSS headquarters. In the event there is no higher CSS headquarters, it positions itself to best support the supported unit commander's concept of operations.*

**f)** *Has its planning accomplished by higher CSS headquarters.*

## C. MOBILE COMBAT SERVICE SUPPORT DETACHMENT (MCSSD)

A MCSSD is task organized from a number of CSS resources and usually supports mechanized operations. The DS CSSD establishes one MCSSD per maneuver element (i.e. RTFs) to provide mobile support for the Ground Combat Element (GCE). The GS CSSD may build up several MCSSDs for mobile support to the Marine Aircraft Wing (MAW) and airfields. The FSSG normally provides the command and control element of the MCSSD. Its primary tasks are to arm, fuel and fix the mechanized force while on the move. It does not establish fixed CSS facilities.

## D. LOGISTICS OPERATIONS COMMAND AND CONTROL CAPABILITY (LOCCC)

Logistics Operations Command and Control Capability (LOCCC) is a concept that is being proposed by Colonel Jeff Grelson, Commanding Officer of Brigade Service Support Group 1 (BSSG 1), and is the proposed alternative concept that is modeled in this thesis. The current operational concept for the CSS is a direct descendant of operational concepts used in the WW II era. Existing service and support units were spread-loaded

across the assault force and the more deliberate CSS capabilities were kept in general support of the force as a whole. Then there was a support area on the beach from which combat units could draw supplies from at will. "Logistics units that were placed in close support of a maneuver unit were task organized from the logistics units at the division level or higher and operated essentially as though they were attached (Grelson 2000)." A similar version of this concept is used today by the CSSD, in which multiple, mirror-imaged MCSSDs are provided to each maneuver element (refer to Figure 2). With a concept such as this, a robust command and control capability was not needed since the CSS units were directly attached to the units they supported. Even if a better command and control concept were built, it would not be more effective unless the CSS operational concept changed. Hence, the LOCCC concept was developed.

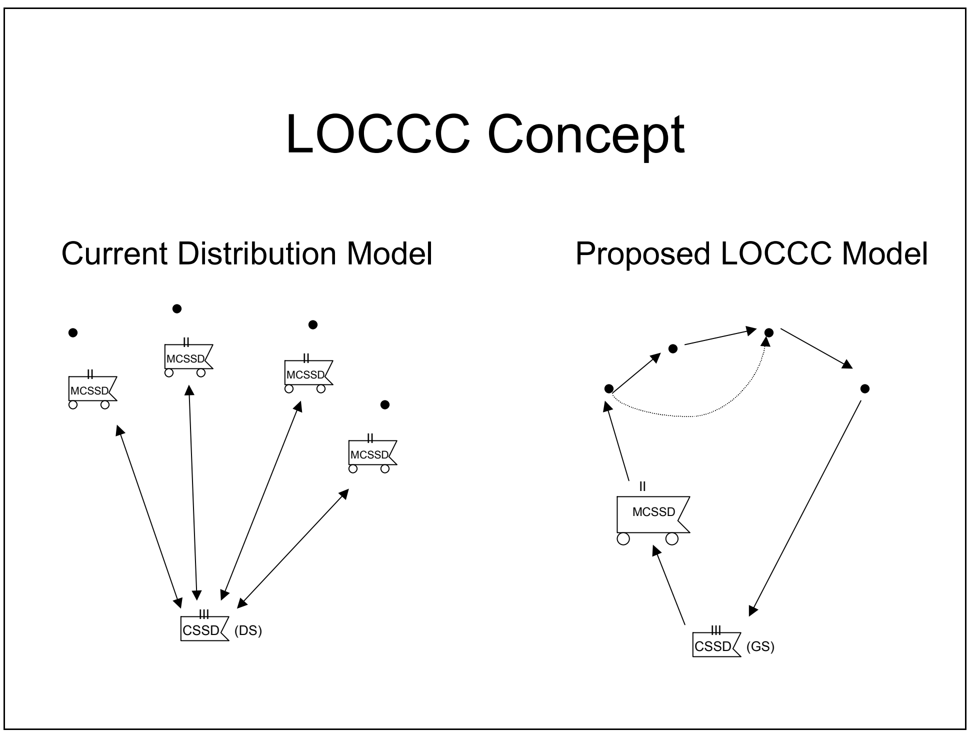


***Figure 2. Logistics Operations Command and Control Capability (LOCCC) Concept (From: Gannon Nov 2000)***

*This figure depicts the two concepts referred to in this thesis. For a more detailed view of the current distribution model refer to Figure 1. The proposed LOCCC model depicts the concept behind the alternative warfighting template.*

The LOCCC concept reverses the current DS/GS ratio. Instead of having a MCSSD for each maneuver element there would only be two MCSSDs; “one that will provide support to the entire GCE in a GS role, and one that will add depth and flexibility to the tactical logistics effort in a DS role (Grelson 2000).” The goal of Colonel Grelson’s new concept is to increase the responsiveness of tactical logistics units through the use of more efficient command and control techniques. One such improved technique under the LOCCC concept is the command element’s ability to communicate directly with the MCSSDs, which allows the MCSSDs to be redirected as needed (refer to Figures 2 and 3). This ability makes more effective use of vehicles through improved vehicle routing. Moreover, it has an additional benefit of reducing the “iron mountain” that must be maintained by the logisticians by replacing considerable quantities of supplies with speed, agility, and accuracy. Using this concept, the Combat Service Support Detachment will no longer require massive quantities of supplies to be maintained at each MCSSD. Instead, vehicles will be routed whenever and wherever they are needed from a central point. This is therefore a vehicle routing problem with additional constraints in the form of time windows.

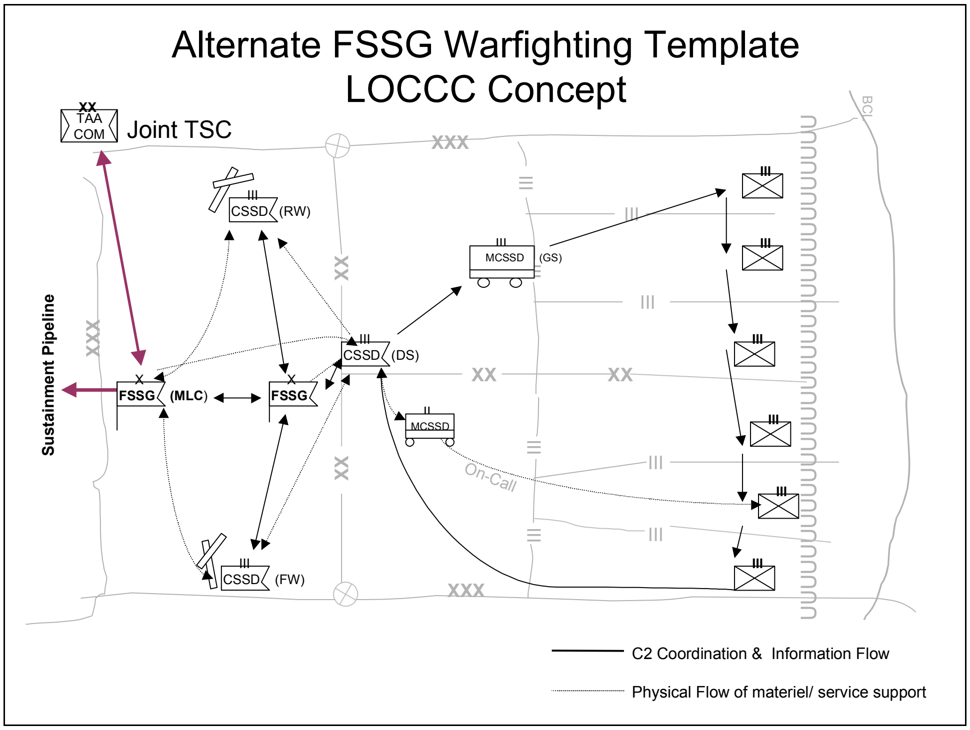


***Figure 3. Alternate FSSG Warfighting Template, LOCCC Concept (From: Gannon Nov 2000)***

*The figure shows a more detailed description of the LOCCC concept. The concept is similar to a traveling salesman problem, as can be observed in the figure. A vehicle attempts to reach all the nodes in the most efficient manner, with the additional benefit of being able to be rerouted if needed.*

## E. RECENT STUDIES

Numerous papers have recently been written on various aspects of how to move supplies from the sea to the shore and how to support troops from the sea with sea based logistics. This falls in line with the Marine Corps doctrine called Operational Maneuver from the Sea (OMFTS). In most AOR's, one flank may be a coast/beach, so sea based logistics may be considered as one of the resource "nodes" for supplying troops ashore. One complication that may arise with sea-based logistics involves the dynamic nature of troop movements. If there is an attack that involves multiple troop movements at the same time then air assets would be completely consumed and leave no lift for supplies (Gue 2000). In this case, supplies would be needed ashore to reduce the need for supply sorties. This would entail the use of more Motor Transportation assets ashore. General Charles C. Krulak, the 31st and previous Commandant of the Marine Corps, specifically stated in his

planning guidance White Paper on OMFTS that Combat Service Support (CSS): "…flow must be efficient, secure, and timely, with the option to remain sea-based or to buildup support areas ashore (Krulak 1997)." This thesis considers such a problem and covers an aspect of the logistics infrastructure ashore.

By covering an aspect of the infrastructure ashore, this thesis stays in line with General James L. Jones' (Commandant of the Marine Corps) vision for the future of the Corps. General Jones and a panel of Marine generals devised a whole new strategy for the Corps dubbed "Marine Corps Strategy 21" with intent on broadening OMFTS. "Operational Maneuver from the Sea is being expanded to include a much broader operational strategy of Expeditionary Maneuver Warfare (EMW). OMFTS envisions the worst-case scenario. 'I have to stay afloat; I have to run sea-based operations' (Brinkley 2000)." Expeditionary Maneuver Warfare is about taking advantage of being able to operate in any clime and place whether you are land-based or sea-based. Reliance on Navy ships is going down (Brinkley 2000). In Marine Corps Strategy 21, General Jones envisions a world where sustaining a force from the sea as OMFTS suggests is the worst-case scenario. Rather he lays out a concept of a Marine Corps that is agile enough to employ a brigade-size force anywhere in the world across the spectrum of operations from any type of expeditionary site. This includes completely land-based or sea-based operations or a combination of the both.

The Office of Naval Research is very interested in studies involving sea-based logistics. It is sponsoring and funding an experimental system by the name of SEAWAY, which will be used for planning, and executing maritime logistics operations mounted from a sea base. SEAWAY will assist in developing plans, modifying plans as needed, making logistic recommendations, identifying conflicts and providing inferences as the situation changes. SEAWAY is being developed by CDN Technologies (Chapman 2000). The ultimate goal of SEAWAY is to establish a flow of supplies and equipment that is timely, predictable, and tailored to the MAGTF/ joint force requirement. SEAWAY should be the tool with which to explore the ramifications of making various logistics decisions and will provide continuous visibility on everything enroute by sea.

Other academic studies have been recently accomplished in the area of sea-based logistics. Captain Scott Allen's thesis presented a spreadsheet model that can be used by Marine logisticians in computing sustainment requirements and the resulting tactical motor transport lift requirements necessary to keep a notional sized maneuver element supported on a daily basis in the Marine Corps' projected maneuver warfare environment (Allen 1995). He used MAGTF II and the Logistics Automated Information System (LOGAIS) for computing requirements to be fed into his model. In contrast, this thesis used LOG2000, an EXCEL spreadsheet model used by the 1st Force Service Support Group (FSSG), to calculate sustainment requirements. Captain Allen found an apparent inconsistency of consumption and usage factors used in computing fuel requirements for various end items. The strength of his model is that it gives the planner a tool to quickly determine sustainment requirements with a clearer picture of what factors are driving the overall requirements.

Factors such as the sustainment requirements that Captain Allen wrote about were used in Lieutenant Mark Beddoes' thesis where he determined the maximum standoff distance of the sea base from shore under different operating conditions (Beddoes 1997). He focused on the Marine Expeditionary Unit (Special Operations Capable) (MEU (SOC)) forces. He allowed for attrition of aircraft in his model and as such showed that the standoff distance would decrease the longer a sustainment mission continued. He showed through his analysis that future aircraft can support Marine forces with smaller logistical demands, such as infiltration type units, but they will not be able to support a traditional ground force mix at standoff distances envisioned.

In a similar study to LT Beddoes', Major Robert Hagan examined sustainment requirements and standoff distances for several landing force scenarios (Hagan 1998). He determined people and equipment required for a mission and went on to determine each force package's sustainment requirements. Major Hagan demonstrated the degree to which aircraft will be able to meet requirements if sustainment is delivered exclusively by air. Analysis revealed several situations where sustainment alone required more than the total number of available sorties.

Captain Norman Reitter then wrote a more detailed spin-off of LT Beddoes' and Major Hagan's masters' theses (Reitter 1999). He produced a stand-alone system to assist planners in determining sustainment requirements of forces ashore. Planners can use his aircraft-scheduling algorithm to manage the aircraft at the sea base and determine if the sustainment plan is feasible. One recommendation for future studies was to look at surface transportation assets to allow multiple delivery modes.

Professor Kevin R. Gue noted that OMFTS emphasized sea-based logistics rather than using large, land based supply points. "The overriding goal of sea based logistics is to minimize or eliminate the need for land-based inventory; and given unlimited air assets, this is easy to do… Unfortunately, the number of aircraft in an expeditionary force is limited, due to space constraints on host ships (Gue 2000)." This is the reasoning behind Professor Gue's article on how to configure the sea based distribution system over time to support a given battle plan with a minimum of land based inventory. One aspect that Gue did not model was the truck assets available for use. Since air assets alone cannot meet sustainment requirements ashore this thesis models truck assets.

Similar to LT Beddoes and Major Hagan, Captain Christopher Frey used discrete modeling to analyze sustainment requirements of forces ashore (Frey 2000). He too observed the effects of aircraft attrition. His study analyzed a much larger size force and delivered sustainment to forces located in more than one location. He also imposed a requirement of sustaining tactical aircraft ashore. He concluded that if the standoff distance of the ship is long (100-170 nm) the delivery of all required sustainment ashore with only aircraft is not feasible. One method to counter the effect of the long ship to shore distance is to deploy a footprint of logistics vehicles ashore carrying sustainment.

The problem addressed in this thesis is similar to the aforementioned studies in looking at supporting sustainment requests of forces ashore. The key factor is that one cannot count on aircraft being available at all times to deliver supplies because extenuating circumstances are likely. All of the above studies revealed that sustainment alone required more than the total number of available aircraft sorties. There will always be a time when the CSSD must utilize the conventional means of Motor Transportation to deliver supplies to forces. This is the next logical step in the logistics infrastructure to

sustain troops. All means of transporting supplies must complement each other. This paper will differ from previous studies in that it will look at the Motor Transportation aspect alone and analyze operational concepts for utilizing the CSSD instead of observing the effects of aircraft on sustainment. The sea-based logistics may just be considered as another supply node in a network.

### F. TRANSPORTATION ASSETS FOR THE CSSE

There are five modes of operation; namely truck, rail, water, air, and pipeline. This thesis is only concerned with the surface aspect, Motor Transportation. "The Marine Corps activates a Force Movement Control Center (FMCC) within theater to coordinate and provide transportation services to all land-based elements of the MAGTF" (Joint Pub 4-01.3 1996).

The transporters that will support movement of supplies for the MCSSD and the CSSD are a combination of rotary wing aircraft and Motor Transportation vehicles. Aircraft use is at a premium and is used at the discretion of the commander in charge of CSS. That is why it will not be considered here. We will only be concerned with ground transportation.

### G. SUSTAINMENT REQUIREMENTS

Daily sustainment requirements are functions of the number of personnel, the number and types of equipment used, and the events / mission taking place. The respective classes of supply determine sustainment requirements needed (MCWP 4-1 1999). The classes of supply are:

- I. Subsistence (Meals Ready to Eat (MREs) and water)
- II. Individual Equipment
- III. Petroleum, Oil, and Lubricants (POLs)
- IV. Construction Materials
- V. Ammunition (W-Ground, A-Aviation)
- VI. Personal Demand Items
- VII. Major End Items
- VIII. Medical Supplies

IX. Repair Parts

X. Non-military Program Material

The focus of CSS is on distribution, arming, fueling, feeding, fixing, and clothing the MAGTF. "History, deployments, and training exercise experience generally holds that the 'top three' CSS efforts are providing for fuel, water, and ammunition (Gannon Feb 2001)." Normal operations require the replenishment of other consumables and repairables, i.e., hydraulic lines for aircraft and repair parts for vehicles. However, only Class I, Class III, and Class V sustainment requirements (food, water, fuel, and ammunition) will be considered in this paper. This is due to the fact that they provide the greatest logistical challenge in nearly every mission.

Logisticians must always provide food (Class I requirements) at a sustained rate. Every soldier must receive enough food to remain combat effective. Rations must be pushed forward at a sustained rate that ensures the soldiers receive enough food without wasting rations and transportation assets. The logistician cannot wait for requests for food to arrive. Such inaction would result in too little too late.

Class III support dictates that fuel tanks and fuel tankers must remain as full as possible in all situations on the battlefield. "An empty fuel truck is a liability, but the same fuel truck becomes an important asset when it is full (Edwards 1993)." Stockage should be maintained at operational levels. Fuel trucks need to be constantly moved from rear to forward areas. A poor situation is when shortages replace a full stock. Combat units must be able to rely on a steady flow of fuel for their operational planning.

The key to Class V support is to have sufficient ammunition at critical points on the battlefield without risking its loss to enemy action (Edwards 1993). Ammunition directly influences tactical operations. Commanders must plan their operations and be fully aware of the support capabilities of the ammunition supply system. Ammunition requirements must be anticipated and demands must be aggressively met. The movement of the massive weights represented by ammunition requires a great deal of planning and foresight.

THIS PAGE INTENTIONALLY LEFT BLANK

# III. CSSE SIMULATION MODEL APPROACH / METHODOLOGY

Logistics in its basic form is simply providing supplies and services to a customer. The challenge is to reduce or eliminate the time from the customer request to when the supplies or services are received. A conceptual laydown overlay of how demand zones and supply points are depicted may be referred to in Figure 4. Visualizing the Combat Service Support snapshot in this manner simplifies a complex problem and allows for intuitive decision making (Gannon Nov 2000).

## A. SCENARIO

The scenario used for this model is an adaptation of a training exercise utilized at Marine Corps Air Ground Combat Center (MCAGCC), Twenty-nine Palms, California. As a reference for building a scenario, the author used an operation dubbed "Steel Knight" which is the Combat Service Support transportation portion of the operation "Desert Knight". The Main Supply Routes (MSR's) that were modeled can be referred to in Figure 5. The roads marked in solid black indicate the MSR's modeled. The units being supported as well as the composition of the supporting units are all notional in an effort to maintain an unclassified status. Unit locations are based upon the author's interpretation and are solely for analyzing the current CSS concept versus the LOCCC concept. The locations of supply points near demand zones may be viewed in Appendix B, Figure 17.

The scenario is not an exact representation of Operation Steel Knight. The purpose of this model is to give an operational perspective of the schemes of maneuver that a Combat Service Support Detachment may utilize. Hence, the composition of supporting or supported units is not the key issue. The key issue is the resulting evaluation of the LOCCC concept.

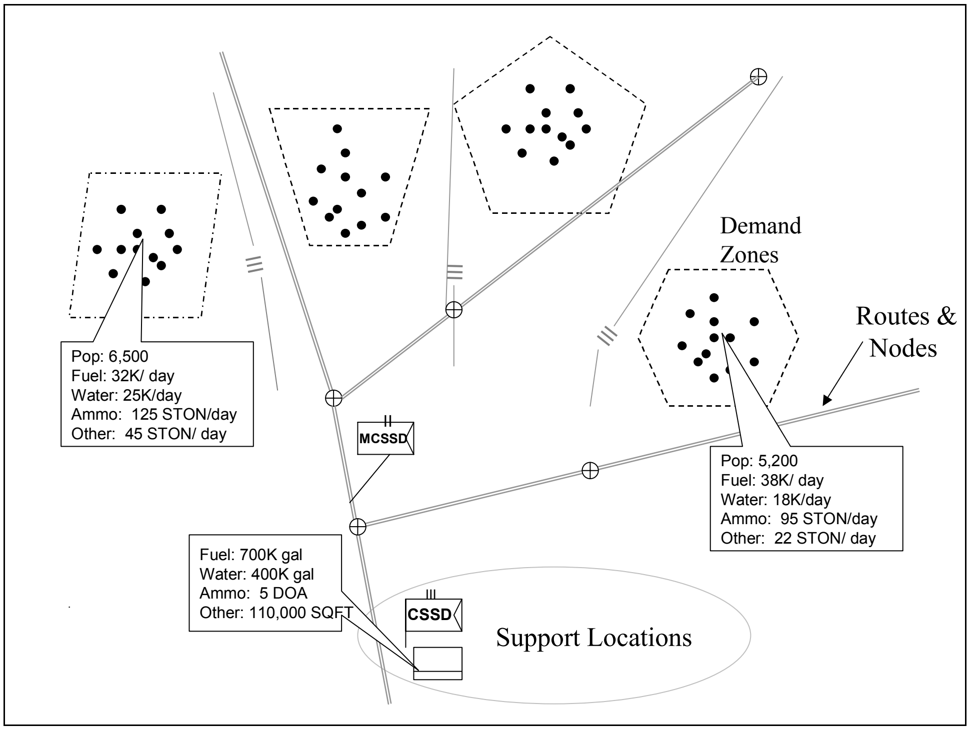


***Figure 4. Conceptual CSS Laydown Overlay (From: Gannon Nov 2000)***

*In the figure, friendly or supported populations are grouped into "zones" of demand, so that rollup level re-supply data can be associated with the zone. Locations of supply points and dumps are depicted, with rollup level data of capacity or storage capability. Finally, a distribution network is shown to identify major routes and nodes. The distribution network links supply locations with demand zones. Visualizing the CSS snapshot in this way simplifies a complex problem, and allows for intuitive decision-making. (Gannon 2000)*

The scenario employed uses a notional Marine Expeditionary Brigade (MEB) sized force. The main element requiring support is a Regimental Combat Team notionally composed of (Adams 2001):

- Regimental Headquarters and 3 Infantry Battalions
- Infantry Weapons Company
- Artillery Battalion and Battalion Headquarters
- Assault Amphibious Vehicle (AAV) Battalion and Battalion Headquarters
- Combat Engineer Battalion (CEB) and other associated units
- Tank Battalion and Battalion Headquarters

- Light Armored Vehicle (LAR) battalion

The units requiring sustainment were placed throughout the MCAGCC in 29 Palms, California. Re-supply locations were situated at intersections of the MSRs modeled in Figure 5.

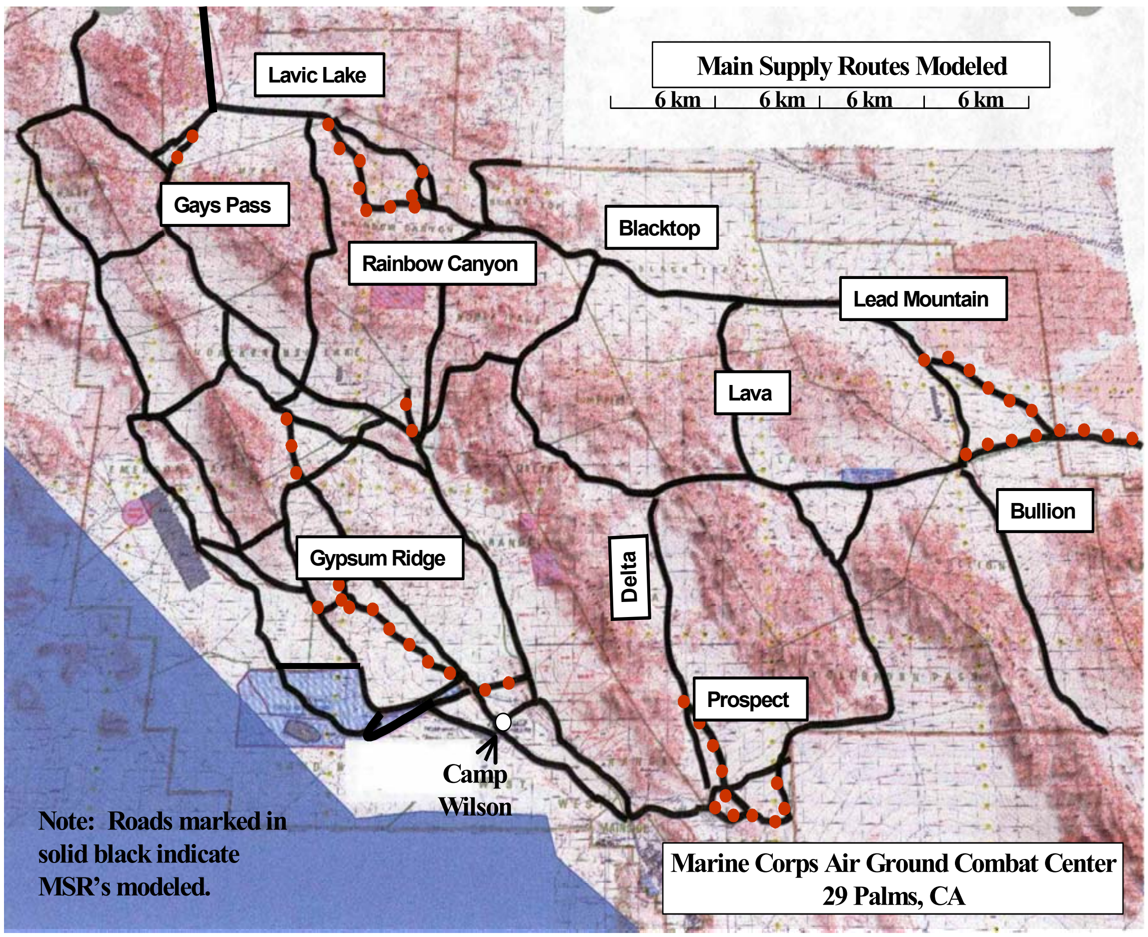


***Figure 5. Main Supply Routes Modeled (From: Parker 2000)***

*The solid black lines in Figure 5 indicate Main Supply Routes modeled in this thesis. The bold dots are areas not modeled due to computational complexity in the development of the model.*

The daily sustainment requirements were taken from LOG2000 (Armstrong 2000). LOG2000 is a Microsoft EXCEL spreadsheet developed by Major Neita Armstrong and is currently used by the 1st FSSG as one of the planning tools for calculating preliminary sustainment estimates. LOG2000 allows for the calculation of CSS requirements given a

task organization. Class I requirements are derived from MSTP Pamphlet 5-0.3 and FM 101-10-1/2. Class III is based upon CNA study from April 2000. Class V is based upon MCO 8010.1E. The total supply class requirements for the Ground Combat Element (GCE) may be referred to in Appendix B. This is further broken down into individual requirements for each of the supported units comprising the GCE.

Scenario A deals with a Marine Expeditionary Brigade (MEB) size force with the main element requiring support being a Regimental Combat Team (RCT). In this scenario, the supported units require a full re-supply within particular time windows. Scenario B deals with the same RCT only this time they only require a partial re-supply consisting of 50% what they requested in Scenario A. Scenario C deals with much smaller task forces only requiring a partial re-supply within their time windows. Data employed in the model for the three scenarios may be viewed in Appendix B.

The stochastic nature of vehicles moving through a road network is dealt with in the scenario by using the gamma distributions for the events that naturally vary with time. Each probabilistic element is discussed in the model structure below. Loading, unloading, possible delays in loading, possible delays enroute such as checkpoints, and designated waiting areas along the route are all events that are varied.

## B. MODEL ASSUMPTIONS

For ease and clarity of the problem scenario and model, the following assumptions and respective justifications limit the scope of the research in this thesis:

1) the locations for the combat units are given and the battle plan has already been made;
2) the demand of fighting units for support is also known, since it is derived from the basic plan of the battle;
3) the MCSSD has been designated by the CSSE commander as its number one priority so if any vehicle goes down for maintenance for over 24 hours it will be replaced;
4) CSSE's have a constant re-supply from sea-based logistics;
5) nuclear, biological, or chemical threat are the norm; and

6) the Department of Defense is capable of sourcing all the necessary supplies that the MAGTF requires at the operational level.

## C. SCOPE AND LIMITATIONS

The background of this paper is the current Marine Corps concept of CSS where one General Support CSSE organizes the support into various Direct Support (DS) organizations that follow in trace of the Ground Combat Element (GCE), (each one in DS to a Regimental Task Force); and overall supported. The paper contrasts that concept to the radically new concept being advocated by Colonel Jeff Grelson of one DS and various GS CSSEs, modeled in this thesis. Limitations to the model are as follows:

1) specific results of the study will only hold true for scenarios with a similar size of deployed forces, and motor transportation availability;
2) the model is built only to re-supply Class I, III, and V sustainment requirements;
3) the driver is separated from the vehicle since he is not a central issue. During wartime a driver will be found if one is needed and people will not be constrained by specific work hours. For example, all available personnel were pressed into driving in order to keep essential support moving forward during Desert Storm (O'Donovan 1991); and
4) consumption rates are deterministic and based on usage rates and planning factors established by the Marine Corps.

## D. MODELING METHODOLOGY USED

A two-step approach was taken to solve the problem presented. First, the Vehicle Routing Problem is solved using optimization software. That model will henceforth be referred to as VRP. Second, the output from the VRP is run through a simulation and analyzed. The simulation methodology is presented first due to the fact that it is fundamentally the focus of the exploratory analysis. It is also a focal point of the optimization model since the simulation actually simulates a route that is selected by the VRP. The data collected from the simulation are also used for the analysis of the LOCCC

concept. The VRP is thoroughly discussed in the next chapter and provides a mathematical basis for the modeling approach used.

The simulation modeled in the thesis used discrete events and was written using the Java programming language and implemented in Simkit. Simkit is a discrete event simulation package authored by Professor Arnold H. Buss and Lieutenant Kirk Stork, United States Navy (USN) (Stork 1996). Simkit is a powerful tool because it provides a wide array of software components which when properly combined produce a robust simulation.

Simulation methodology was chosen in order to take this thesis beyond the non-stochastic modeling of the Vehicle Routing Problem with Time Windows that was developed for this thesis using the General Algebraic Modeling System (GAMS). The world is stochastic and by taking the extra step to simulate the road network chosen through the use of GAMS code the model takes into account the stochastic nature of the problem. A discrete event simulation models many of the dynamic aspects of a vehicle routing problem.

This thesis also used the Extensible Markup Language (XML), which streamlined the process for manipulating data in the road network through the use of a Document Object Model (DOM) parser rather than using large properties files (McLaughlin 2000). An XML document provides greater maneuverability within a large pool of data. For instance, the DOM provides an easy to use, clean interface to data in a desirable format. By using XML, it was also simpler to directly work with a Konig graph from which data could be manipulated as well (Jackson 1999). XML also provides greater flexibility by allowing other sources of data to easily be input into an XML document for use in the simulation without changing any source code.

The Java programming language has an inherent modeling flexibility because it uses object-oriented programming (OOP). OOP allows users to more easily modify and augment the model (for example, it is possible to change network characteristics by modifying only one part of the model). Java is platform independent so users have the flexibility to run the program on a variety of computers. Object-oriented programming added much flexibility to this thesis by allowing templates for creating multiple instances

of an object such as a vehicle and still has that same object differ in its properties. Hence, a HMMWV, a LVS, or a Five Ton Truck could be created from the same template and still be identified by its individual properties. The same flexibility was given through OOP when it came time to create templates that could be used for the loading or unloading of the different vehicle types.

## E. MODEL STRUCTURE

The basic flow of information for the simulation model can be seen in Figure 6. Modeling the road network is accomplished one time after receiving the mission. In this case the road network modeled is 29 Palms. OOP allows different road networks to be modeled in the future if it is desired. The number ‘2’ in the Figure 6 refers to part of the data that is input into the Vehicle Routing Problem (VRP) model in GAMS. Upon receiving the information, the optimization model solves the vehicle routing problem with time windows under the LOCCC concept and produces appropriate routes that the simulation model utilizes. The simulation models the vehicles traveling through the given routes to include loading, unloading, and delays. The data from the model provides a basis for the feasibility of this vehicle routing structure and highlight its strengths; i.e. flexibility, timely delivery and usage of resources, route streamlining, and less build-up of supplies. The simulation runs through multiple loops in order to obtain confidence intervals on the data collected. This is indicated by the ‘loop’ in Figure 6.

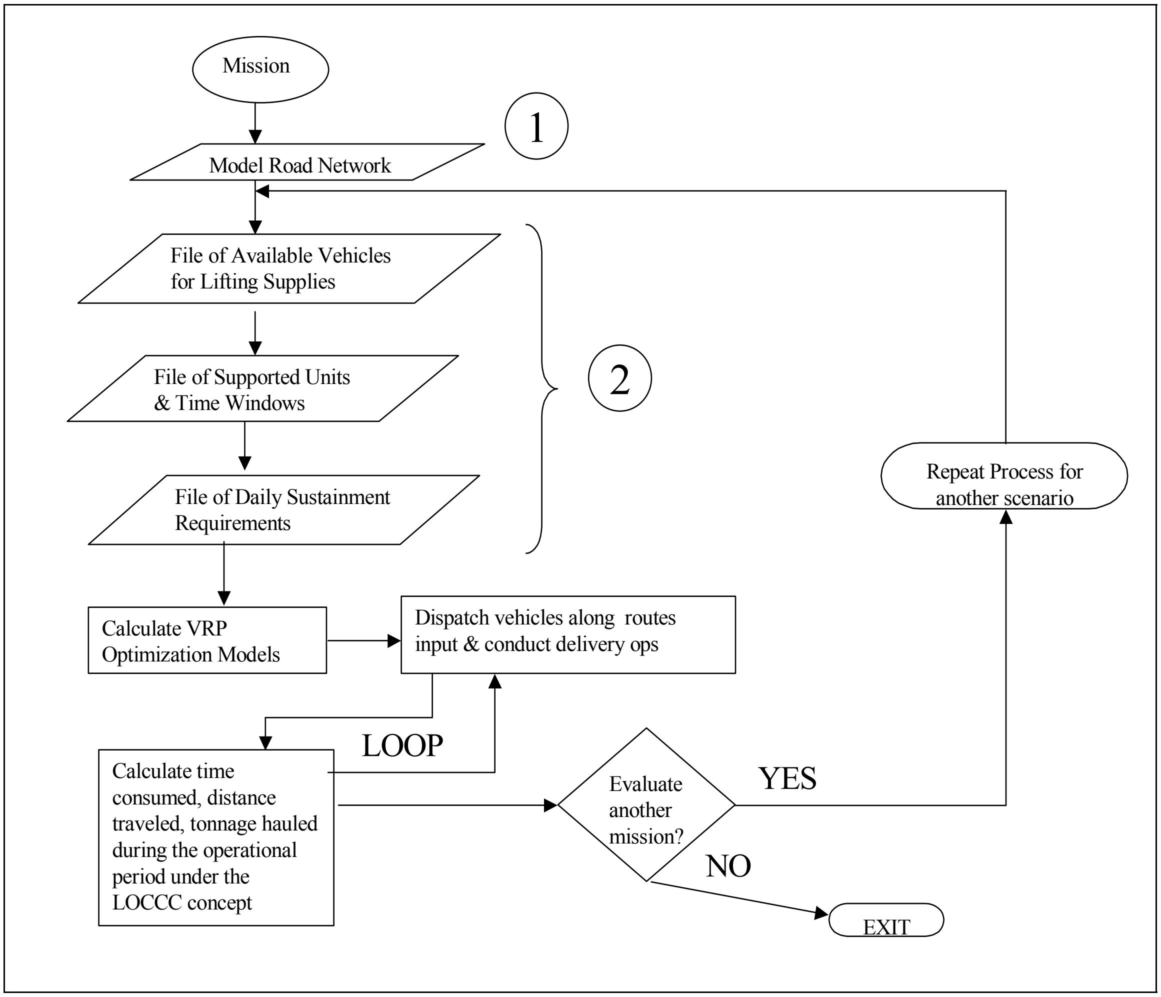


***Figure 6. Flowchart Overview of Combat Service Support Operations Center (CSSOC) Simulation Model***

*This figure depicts how data flows to make the simulation possible. Number 1, model the road network, is done one time. Number 2 is input into the Vehicle Routing Problem model. The loop is representative of multiple runs in order to obtain confidence intervals on data collected.*

### 1. Probabilistic Elements

Uncertainty is an important aspect in any simulation model since a simulation is an attempt at modeling the stochastic nature of an event or situation. Uncertainty enters the model in several areas. It was not possible to obtain data on the random variables of interest in this simulation. The distributions were selected in an ad hoc manner as shown below, but the model may easily be reconfigured for other distributions without recompilation.

#### a) *Loading Times*

Loading times are based upon the Combat Service Support Field Guide, and are modeled with a triangular distribution (Law & Kelton 2000). Semi trailers and straight trucks take approximately 2.5 hours of loading and unloading per round trip. Container transports take 1.5 hours per round trip (Edwards 1993). An interval was identified with subjective estimates of optimistic, pessimistic, and most likely values of load times. The most-likely being the times given in the Combat Service Support Field Guide.

#### b) *Unloading Times*

The unloading times are modeled with a gamma distribution. The LVS and the five-ton truck are given a mean time to unload of 1 hour with a standard deviation of 42 minutes. A HMMWV is given a mean of 18 minutes with a standard deviation of 12.7 minutes.

#### c) *Possible Delays in Loading*

Possible delays in loading are modeled to occur 50% of the time through the use of the gamma distribution. The characteristics of the gamma distribution used consist of a mean of 10 minutes and a standard deviation of 0.67 minutes. A delay may occur any time during a loading evolution.

#### d) *Possible Delays Enroute*

Possible delays enroute are modeled to occur 10% of the time through the use of the gamma distribution. The characteristics of the gamma distribution used consist of a mean of 10 minutes and standard deviation of 2 minutes. This is used to simulate the possibility of reaching a checkpoint or other such delay.

#### e) *Designated wait times along a route*

This was programmed into the simulation and the Vehicle Routing Problem in order to assist in meeting all the required time windows for delivering. It is not desired to allow the vehicles to arrive too early or too late to the time window of a demand zone.

A driver may be given a set of orders to deliver a commodity within a specific time window so the driver or the dispatcher attempts to time it in such a way as to meet all time windows. The gamma distribution was used to model this probabilistic element. The mean ($\alpha\beta$) of this distribution is the designated 'Wait' time given by the optimization model. The shape ($\alpha$) of the gamma distribution is fixed for the entire set of vehicle types so the standard deviation, $\beta * \alpha^{1/2}$, changes accordingly as the mean changes for this probabilistic element.

### 2. Parsing and Obtaining Information from the Network

Input for the road network is obtained in the Java software by two classes, FileGrabberArcs and FileGrabberNodes. This information is then converted from the VRP into a complete road network file in the XML. This procedure enabled the process for obtaining information from the road network as it is needed to be streamlined. That same file was then parsed for use by another element in the Java software that was built. Any information needed about the network may be obtained from this class. Given a coordinate, a node may be found or given a node, a coordinate may be found. Arc lengths may also be obtained from this class

.

### 3. Obtaining Information from Vehical Routing Problem Output

All of the information from the output of the Vehicle Routing Problem model is obtained and organized in the Java class FileGrabberRoute. FileGrabberRoute makes extensive use of the TreeMap object in order to organize the data obtained from the optimization model. Vehicle waypoints, loading orders, unloading orders, requisition data, unmet demand quantities, and vehicle trip tickets are all obtained from this class. The trip ticket indicates waiting points along a route in order to meet all time windows.

### 4. Time, Speed, and Distance Conversions

Numerous conversions must take place with time, speed, and distance when transferring data and results from the VRP optimization to a Java simulation. The optimization model used a time step of 20 minutes per step. The VRP program provided

the simulation model with information on which road network to use, as well as when and where commodities should be delivered. Each time period of information passed to the simulation was directly linked to the time steps used in the VRP. The simulation model works in hours. This created a necessity to convert all the time steps so essentially all clocks were synchronized.

The simulation was written to work with coordinates Latitude and Longitude in seconds. The VRP model worked with distances in kilometers. This created the necessity to convert distance to seconds and speed to seconds per hour. The speed and distance program did just that with a simple calculation based upon the type of distance used (e.g. miles, kilometers). Note that 'seconds' refers to geographical distance, not time.

#### 5. Properties File Sorter

In order to deal with different vehicle types, properties files were created for each one. If another vehicle type is needed then all that is needed is a new properties file and the program will accept it. In order to do this, a properties file sorter was created that could sort through all the properties files that are available. This file works with another Java software class called VehicleIdentifier. If a mover reaches an event that requires a properties file then a Java software class, PropsFileSorter, looks at the mover, obtains its name, identifies it through VehicleIdentifier, and returns its appropriate properties file.

#### 6. Movers and Mover Managers

PathMoverManagers are created for every mover in order to keep track of waypoints and move to the next appropriate waypoint. Since travel is along a series of roads, straight-line distance is not desired when moving from waypoint to waypoint in the network. A 'Mover' simulation entity was routed from which distances between two nodes were determined by the corresponding arc. Every Mover has a corresponding Mover Manager that directs the Mover through its waypoints.

### 7. Loading, Serving, and Dispatching

Every mover has a Java software class VehicleContainer that holds its cargo. If the command to load is given then the mover looks at its load orders and increments or decrements the payload without going beyond the maximum quantity the vehicle may carry. The Java software class ServeTheMatl class operates in the opposite direction, incrementing the VehicleContainer when directed to unload and incrementing the customer requirement by the quantity unloaded.

### 8. Overview

The simulation model was built in such a manner that allows it to be expanded in future iterations of this thesis. This model takes the critical elements needed in order to conduct a proper loading, traveling, and distribution sequence. This allows a complete analysis to take place. The next chapter shall discuss the optimization model utilized as the underlying model of this simulation.

# IV. VEHICLE ROUTING PROBLEM WITH TIME WINDOWS

This chapter designs and develops the underlying optimization model that is used in the discrete event simulation.

## A. PROBLEM

The Vehicle Routing Problem (VRP) with Time Windows is given by a set of vehicles V, a special node called the CSSE, a set of units to be supported (customers), and a directed network connecting the CSSE and the customers. The VRP is a well-known problem and is highly documented and studied (Golden and Assad 1988). Exact and heuristic algorithms have been used to solve this problem (Laporte 1992). Besides the time windows requirements, our VRP has some special features such as vehicle capacity for each commodity and cargo incompatibility (e.g. fuel and ammunition) that has not been accomplished before in this field of study.

There are k vehicles. Each node is treated as a potential customer. If a customer does not reside at the present node then demand is treated as zero. There are n+1 customers since the CSSE will be denoted as node zero. A travel time is associated with each arc of the network. Travel time is proportional to the distance of the arc and the average speed of the vehicle. The rate of movement for all vehicles in this model is a constant 15km per hour. Travel time is also based upon a time period or time step of 20 minutes, so an operational day of 14 hours would be comprised of 42 time-steps. For this reason, travel time may be factored up or down depending upon the unit time-step that is used. Travel times are rounded to the nearest integer multiple of the time period unit.

Vehicles have limited capacity depending upon the commodity and vehicle type. Customers also have varying demands that must be met within pre-defined time intervals, denoted by an earliest arrival time and latest arrival time. The time to make a delivery is based upon the vehicle type and the demand node. In a more detailed situation this number would be a decision variable because loading and unloading times also depend upon the quantity of cargo loaded on a vehicle.

A sequence of legs (represented by arcs in the network) comprises a route for the vehicle. Vehicles are restricted to deliver within a time window based upon the earliest and latest arrival times. Those vehicles arriving earlier than the earliest arrival time may incur waiting. Vehicles are required to complete their routes within a total route time and to return to the CSSE before the last period of the study.

Specific rules apply to some types of vehicles. For example, for security reasons, vehicles of type LVS or FTON cannot be loaded with ammunition and fuel at the same time.

The objective of the Vehicle Routing Model (VRM) is to obtain an optimal vehicle routing that minimizes a weighted function of the customers' unmet demand while all the conditions stated above are satisfied. This solution will be transferred to the simulation model for further analysis of those details that have not been included in the model: variable loading and unloading periods for the vehicles, variable wait times along the route and possible checkpoints, possible delays during a loading evolution, and a refined time period unit. The refined time period unit points specifically at the fact that the optimization model uses time steps of 20 minutes whereas the simulation model deals with discrete events so it may use the exact time when an event occurs.

We have included some extra penalty-terms in our objective function in order to ensure that the vehicles do not wander around aimlessly. The penalty-terms in conjunction with the constraints of the model also ensure that the vehicles only deliver at nodes that demand sustainment requirements. These terms are small enough to guarantee that they do not influence the total unmet demand, which is our ultimate goal.

## B. FORMULATION

The model may be mathematically stated as follows:

### 1. Sets and Indices

$T$, set of time periods, $t \in T$

Note: Time periods must be indexed as $T = \{1,2,\ldots,|T|\}$

$C$, set of commodities, $c \in C$

$V$, set of vehicles, $v \in V$

$M$, set of truck types, $m \in M$

$N$, set of nodes in the network, $i, j \in N$

Note: Node $0 \in N$ and is assumed to be the origin of all the vehicles.

$A$, set of arcs in the network, $a = (i, j) \in A \subset NxN$

## 2. Data

$type_{vm}$, parameter that takes the value 1 if vehicle $v$ is a truck of type $m$ and 0 otherwise.

Note: Each vehicle falls in one and only one type, i.e., $\sum_{m \in M} type_{vm} = 1$, $\forall v \in V$

$dem_{ic}$, demand of cargo c at node i (Short Ton (STON))

$trav_{ij}$, travel time between node i and j through arc $a$=($i$,$j$) for $(i, j) \in A$ (number of time periods)

$maxT_v$, maximum route time allowed for vehicle v (number of time periods)

$q_{vc}$, capacity of cargo $c$ in vehicle $v$ (STON).

Note: This parameter is calculated as $q_{vc} = \sum_{m \in M} type_{vm} q^{mc}$, where $q^{mc}$ is a given capacity of cargo $c$ for vehicles of type $m \in M$

$\max q_v$, maximum capacity of vehicle $v$ (STON)

$early_i$, earliest delivery time for node $i$ (time period)

$late_i$, latest delivery time for node $i$ (time period)

$b_{iv}$, unloading time at node $i$ for vehicle $v$ (number of time periods)

Note: This parameter is calculated as $b_{iv} = \sum_{m \in M} type_{vm} b^{mi}$, where $b^{mi}$ is a given unloading time at node $i$ for vehicles of type $m \in M$

$\beta_{ic}$, penalty per unit of unmet demand of cargo $c$ at node $i$ (regret/STON)

Note: Regret is a weight set up as a penalty in order to ensure unmet demand is minimized as much as possible. It may potentially be used in order to establish priorities on which sustainment requirement should be fulfilled first. In all our examples the penalty was arbitrarily chosen at 1 for all nodes and cargoes. This should be further refined for future models in order to establish priorities as may fit a certain scenario or unit requesting a re-supply.

*bigM*, big scalar used in calculations for loading the LVS and FTON trucks (if exist).

Note: Our choice of bigM is $bigM = \sum_{i \in N} \sum_{c \in C} dem_{ic}$ , which is large enough to accomplish its purpose in the formulation (see below) and is numerically tractable for the computation.

$minA_i$, minimum arrival time at node $i$ (time period)

Note: $minA_i$ is defined to help to reduce the number of variables needed in the model. It can be calculated by solving (or conservatively estimating) the shortest route from node 0 to node $i$ in the network.

$fuel_v$, fuel capacity of each vehicle (time period)

Note: Vehicles are tracked by gallons per hour instead of miles per gallon.

$\varepsilon$, small value used in the objective function to discourage vehicles from making unnecessary trips. In all our examples $\varepsilon$ is chosen as 0.00001, which suffices to accomplish that goal.

## 3. Decision Variables

**<u>Binary Decision Variables</u>:**

$X_{vijt}$, 1 if vehicle $v$ starts trip through arc $(i, j) \in A$ in time period $t$

$W_{vit}$, 1 if vehicle $v$ is waiting at $i$ in time period $t$

$D_{vit}$, 1 if vehicle $v$ starts delivering cargo at $i$ in time period $t$

$LW_v$, 1 if vehicle $v$ acts as an LVS or Fton that transports water

$LF_v$, 1 if vehicle $v$ acts as an LVS or Fton that transports fuel

**Non-negative Decision Variables:**

$S_{vict}$, quantity of cargo $c$ served by vehicle $v$ at node $i$ in time period $t$ (STON)

$L_{vc}$, quantity of cargo $c$ loaded in vehicle $v$ (STON)

$U_{ic}$, unmet demand of cargo $c$ at node $i$ (STON)

## 4. VRP Model Mathematical Formulation

**Minimize**

$$\sum_{i \in N} \sum_{c \in C} \beta_{ic} U_{ic} + \sum_{v \in V} \sum_{(i,j) \in A} \sum_{\substack{t \in T | \\ t > late_i}} \varepsilon X_{vijt} + \sum_{i \in N} \sum_{v \in V} \sum_{\substack{t \in T | \\ early_i \leq t \leq late_i}} \varepsilon D_{vit} \quad (1)$$

**Subject To:**

$$\sum_{\substack{i \in N | \\ dem_{ic} > 0}} \sum_{\substack{t \in T | \\ early_i \leq t \leq late_i}} S_{vict} = L_{vc}, \quad \forall v \in V, c \in C \quad (2)$$

$$S_{vict} \leq dem_{ic} \, D_{vit}, \qquad \forall v \in V, i \in N, c \in C \mid dem_{ic} > 0 \vee early_i \leq t \leq late_i \quad (3)$$

$$\sum_{\substack{t \in T | \\ early_i \leq t \leq late_i}} \sum_{v \in V} S_{vict} + U_{ic} = dem_{ic}, \qquad \forall i \in N, c \in C \mid dem_{ic} > 0 \quad (4)$$

$$\sum_{c \in C} L_{vc} \leq max\, q_v, \qquad \forall v \in V \quad (5)$$

$$W_{vit} + D_{vi,t-b_{iv}+1} + \sum_{\substack{j \in N | \\ (j,i) \in A}} X_{vji,t-trav_{ji}+1} = W_{vi,t+1} + D_{vi,t+1} + \sum_{\substack{j \in N | \\ (i,j) \in A}} X_{vij,t+1},$$

$$\forall v \in V, i \in N, t \in T \mid t < |T| \quad (6)$$

$$LW_v + LF_v \leq 1, \qquad \forall v \in V \mid type_{"FTON",v} = 1 \wedge type_{"LVS",v} = 1 \quad (7)$$

$$L_{v,"water"} + L_{v,"ammo"} \leq bigM * LW_v, \; \forall v \in V \mid type_{"FTON",v} = 1 \wedge type_{"LVS",v} = 1 \quad (8)$$

$$L_{v,"fuel"} \leq bigM * LF_v, \qquad \forall v \in V \mid type_{"FTON",v} = 1 \wedge type_{"LVS",v} = 1 \quad (9)$$

$$\sum_{\substack{j \in N | \\ (0,j) \in A}} X_{v,0,j,t-\max T_v} \leq W_{v,0,t}, \qquad \forall v \in V, t \in T \mid t \geq max\, T_v \quad (10)$$

$$\sum_{\substack{i,j\in N|\\(i,j)\in A}}\sum_{t\in T} trav_{ij} X_{vijt} \le fuel_v \,, \qquad \forall v \in V \tag{11}$$

$$X_{vijt} + X_{vji,t+trav_{ij}-1} = 1 \,, \ \forall v \in V,\, i, j \in N, t \in T \mid (i,j),(j,i) \in A \tag{12}$$

$$W_{v,0,1} = 1 \,, \qquad \forall v \in V \tag{13}$$

$$W_{v,0,|T|} = 1 \,, \qquad \forall v \in V \tag{14}$$

$$W_{vit} = 0 \,, \qquad \forall v \in V, i \in N - \{0\}, t \in T \mid t = 1 \vee t < min\, A_i \tag{15}$$

$$X_{vijt} = 0 \,, \qquad \forall v \in V, (i,j) \in A, t \in T \mid t = 1 \vee t < min\, A_i \tag{16}$$

$$D_{vit} = 0 \,, \qquad \forall v \in V, i \in N, t \in T \mid t < \min\{early_i, min\, A_i\} \vee t = 1 \tag{17}$$

$$L_{vc} \le q_{vc} \,, \qquad \forall v \in V, c \in C \tag{18}$$

$$V_{vijt}, W_{vit}, D_{vit}, LW_v, LF_v \in \{0,1\}, \qquad \forall v \in V, (i,j) \in A, i \in N, t \in T \tag{19}$$

$$S_{vict}, L_{vc}, U_{ic} \ge 0 \qquad \forall v \in V, i \in N, c \in C, t \in T \tag{20}$$

## 5. Description of the Formulation

The objective function (1) minimizes the weighted quantity of unmet demand for all the customers served. A penalty is assessed for vehicles meandering and not delivering any commodities. Vehicles also incur a charge of a small penalty for every delivery that is made. This prevents the vehicles from making any notional deliveries. These penalties are negligible enough to not affect the purpose of the objective function of minimizing unmet demand.

Constraint (2) ensures that each vehicle delivers exactly what was loaded on that particular vehicle. This implies that the quantity of a certain commodity loaded on all of the vehicles may not exceed the total demand for that commodity. Constraint (3) ensures that (a) each vehicle does not unload more cargo than required at the node, (b) the delivery is done during the appropriate time window for that node, and (c) the delivery is only made if the vehicle status permits a delivery to start. Constraint (4) keeps tally on whether demand at a node point is served or unmet. The equality in this equation also ensures that all the vehicles do not unload more cargo than required at the node over the planning time. Constraint (5) ensures vehicles are not loaded over their maximum capacities.

Equation (6) is a balance constraint and guarantees that at most one state occurs for each vehicle in every time period (refer to Figure 7). The left-hand side of the balance equation accounts for the present and past, while the right-hand side accounts for the impact of the past decisions in the future. For example, if the vehicle started a trip from node $j$ to node $i$ on time $t\text{-}trav_{ji}+1$, then the vehicle will wait, deliver or start another trip at node $i$ in time period $t+1$. It is important to note that variables $D$ and $X$ take on the value of 1 only when the delivery or trip begins, but not during the remaining time periods.

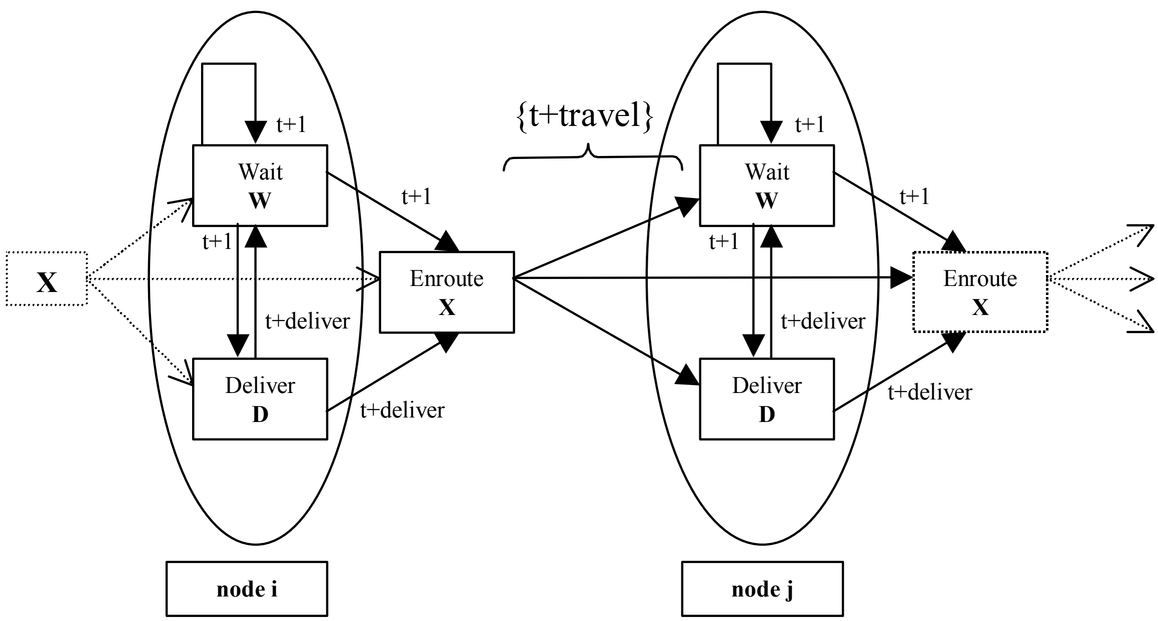


***Figure 7. Network Design for Vehicle Routing Problem with Time Windows***

*This figure depicts the transitions among the possible states a vehicle may take. At a given node a vehicle may be "waiting" (simply staying at the node) or "delivering" (staying at the node and unloading part of the cargo). A vehicle traveling between nodes is in an "Enroute" state.*

*If at time period t the vehicle is waiting at node i then, at time t+1, it may either continue to wait at the same node (e.g. until troops arrive), proceed to deliver or depart to a different node j. Once a delivery starts it continues until finished. Then the vehicle either returns to a "Wait" status or departs to a different node. Finally, a vehicle that starts moving from i to j will continue traveling until it arrives at node j. Then, the vehicle may once again stop and wait, start to deliver at j or continue from j to a different node.*

Equations (7) through (9) are used to ensure that fuel and water as well as fuel and ammunition may not be transported together on an LVS or a Five Ton vehicle. Equation (7) allows each vehicle of type LVS or FTON to act as one of the following three categories: "water & ammunition vehicle", "fuel vehicle", or none of the above. Equations (8) and (9) ensure that each vehicle loads only the allowed type of cargo specified by (7).

Constraint (10) ensures that vehicles do not operate longer than a specified time period. This accounts for the maximum crew day for a driver operating a vehicle. Constraint (11) ensures that the vehicles may not be operated for a longer period of time than they have fuel available. This is based upon the maximum time a vehicle may travel due to fuel limitations. Fuel tank capacities / gallons per hour of LVS', five tons, and HMMWVs are 150 gallons with 16.66 gallons per hour (gph), 78 gallons with 11.5 gph, and 25 gallons with 1.7 gph respectively (TM11 240-15/4B 1994). A simple calculation reveals that the maximum operating hours based upon fuel available is 9 hours for an LVS, 6.8 hours for a five ton, and 14.7 hours for a HMMWV. The maximum crew day is ten hours in this model.

Constraint (12) is intended to strengthen the model formulation by restricting vehicles from backtracking.

Equations (13) through (17) are all the initial conditions: All the vehicles start at node "0" under a "waiting" status, (13), and need to be back to "0" by the end of the planning time, (14). This accounts for an entire operational day. Equalities (15) through (17) impose no active status upon any node, except the origin, before the minimum arrival time. This is because it is materially impossible for any vehicle to arrive at a node before the arrival time specified.

Constraint (18) specifies an upper bound to the vehicle capacity for each type of commodity preventing the vehicle from loading more than it is capable of carrying of that commodity.

Finally, constraints (19) and (20) impose appropriate domains for the decision variables.

The VRP Model prevents the solution from acting counter to logic. As programmers, we took into account various problems associated with the current mode of operations. This model does not allow backtracking of vehicles, resulting in an efficient route. Also, there are not multiple points of origin, hence simulating the reduction of the "metal mountain" of supplies. This naturally eliminates confusion on where to obtain supplies. "Deadheading," the travel of empty trucks to delivery, is also eliminated. Most of all, modeling the circuit GS-heavy approach reduces unneeded infrastructure and adequately serves the units requisition necessities.

## C. A HEURISTIC METHOD TO SOLVE VRP

VRP can become very large and difficult to solve and is best solved by heuristics. We have devised a heuristic that reduces, in part, the computational burden of the original problem.

Our heuristic takes a myopic approach at solving the vehicle routing problem. The program allows the user to divide the number of vehicles available into any group size desirable. If the group size equals the number of vehicles available then the model searches for an optimal solution as if no heuristic existed. If the group size is any number smaller than the number of vehicles available then the program searches for an optimal solution using just those vehicles in the group specified. The vehicles in the heuristic are myopic: they do not know that any vehicles will be arriving in the future so the heuristic attempts to meet as much demand as possible using just those vehicles in the current group specified. All the unmet demand from the first group becomes the new demand for the follow-on group of vehicles. The procedure continues through all groups of vehicles minimizing the unmet demand from the previous group.

This approach has some limitations. The heuristic method does not guarantee the convergence to an optimal solution. Moreover, the heuristic solution may depend on the groups configuration. However, this would still be the same case for a CSSD: The dispatcher would use vehicles that are available at the time to fulfill any demands that are requested in the most efficient manner possible. A dispatcher cannot wait for vehicles that have been promised to arrive at some future time. This leads to the fundamental question of what is a sensible order for the vehicles in the model. Making the group size equal to

the total number of vehicles guarantees an optimal solution to the VRP. A difficulty with this choice is that the model could take a long time to be solved, and in some cases it would be impossible due to limited computational resources. In our computational experience we have used groups of 2 and 4 vehicles for the heuristic. The CPU time is markedly less and the heuristic gives answers very similar to the exact method.

Another inconvenience of the heuristic is that we do not have a lower bound to guarantee the quality of the solution obtained with this method. A basic lower bound can be obtained by solving the linear relaxation of the whole model (including all vehicles). In some cases this can be far from the heuristic solution. However, this can also be the case when using the exact method, because the CPU time to obtain an integer solution close to the lower bound can be very large.

The steps to the heuristic are listed below.

*Heuristic VRP Algorithm*

*Step 1*: Select the sizes of each group of vehicles to be viewed during each iteration of the heuristic;

*Step 2*: If all vehicles have been routed go to Step 5, else for all unrouted vehicles look at vehicles in the group for the current iteration;

*Step 3*: Solve the problem for the current group of vehicles;

*Step 4*: Reset the demand needed to the quantity of unmet demand.
Go to Step 2;

*Step 5*: All vehicles have been routed.
Output results.
Stop heuristic.

## D. COMPUTATIONAL RESULTS

This section describes the computational results for our exact and heuristic methods to solve our model VRP. All computation is performed on a 1 GHz Pentium III computer with 1 Gb of RAM, running under Microsoft Windows 2000. Models are generated using GAMS (Brooke et al. 1998) and solved using CPLEX Version 6.5 (ILOG 1999), with optimality tolerance set at zero and computations halted upon reaching a maximum computational time of 10 hours or an absolute gap inferior to 5 units of penalty in the objective function. Since our regret value is $\beta_{ic} = 1$, the objective function units may be viewed as Short Tons (STONS) of unmet demand (disregarding the small penalty terms).

### 1. Test Cases: Data

The data describe a hypothetical deployment of a Marine Expeditionary Brigade (MEB) sized force. The scenario is as described in Chapter III. Total supply class requirements and the summary of the demand zones may be viewed in Appendix B. We consider a 14-hour operating day $T = \{1,2,...,42\}$, where each time period accounts for 20 minutes of real time. All supply points/ dumps near the demand zones that are used in the scenarios may be referred to in Figure 8 located in Appendix B as well. A total of 22 vehicles available for transporting supplies were utilized for all the scenarios. They consisted of 14 LVS', 5 Five Ton Trucks, and 2 HMMWVs. This transportation support is similar in scope to the typical Table of Equipment for Transportation Support as outlined in the BSSG-1 Commanding Officer Confirmation Brief for Exercise Desert Knight/Steel Knight – 01 (Parker 2000). Numerous versions of the different vehicles exist and perform different missions; we grouped the vehicles utilized into the three categories mentioned in order to simplify the problem. Scenarios used are not an exact representation of the exercise mentioned. Locations of the demand zones for the units are based upon the author's interpretation and are solely for analyzing the concepts modeled.

Scenario A deals with a MEB size force with the main element requiring support being a Regimental Combat Team (RCT). In this scenario, the supported units require a

full re-supply within particular time windows. Scenario B deals with the same RCT only this time they only require a partial re-supply consisting of 50% of what they requested in Scenario A. Scenario C deals with much smaller task forces only requiring a partial re-supply within their time windows. Data employed in the model for the three scenarios may be viewed in Appendix B.

The transportation of liquids in sixcons is built into the formulation. Sixcons are modeled through the use of the $q_{mc}$ capacity data for capacity of $c$ in vehicle type m. Sixcons have a capacity of holding 900 gallons of liquid. Fuel has a weight of 7 lbs/gallon (MSTP 5-0.3 1999) and water has a weight of 8.3453 lbs/gallon (Jordan 2001). A regular 5 Ton may transport 1 sixcon with 900 gallons of liquid. This equates to a capacity of 3.15 STONS fuel or 3.76 STONS water. An LVS with a tandem tow may transport 5 sixcons with one pump, which weighs 2300 lbs. This equates to a capacity of 15.75 STONS fuel or 18.78 STONS water. A HMMWV cannot transport any sixcons.

## 2. Test Cases: Results

### a) *Problem Dimensions*

Our model is a mixed-integer problem with a very high computational complexity. After the simplifications described above and some others (such as variable elimination) made by our knowledge of the problem, our test cases involve 169,178 equations, 179,185 continuous variables, and 165,412 binary variables. Problems of this sort are classified as one of the most difficult problems to solve (NP-Hard) (Nemhauser and Wolsey 1988) and are typically solved through the use of heuristics (Bramel and Levi 1997, Savelsberg 1985, Solomon 1987).

### b) *Problem Results*

The following tables show, for every scenario and vehicle block-size, the unmet demand and cumulative time needed through the iterations of the heuristic algorithm. For the exact method, we indicate the absolute gap (maximum absolute

difference to the best possible solution). In the heuristic algorithm, some of the sub-problems involved were stopped after a number of integer solutions found or maximum computational time to keep them from searching (indefinitely) for an optimal solution. It is noted that an optimal solution at any iteration of the heuristic does not guarantee the optimality of the heuristic solution. The optimality degree of the heuristic solution is learned by observing lower bound of the exact method.

V1 through V3 represent HMMWVs, V4 through V8 represent Five Ton Trucks, and V9 through V22 represent LVS' in all of the scenarios.

**Scenario A**

Total Original Demand: 304.84 STONS

*Heuristic Block Size of 2: (Refer to Appendix C, Figure 19.)*

| Vehicle Group | Unmet Demand | Cumulative Time (min) |
|---|---|---|
| V1 – V2 | 302.26 | 0.44 |
| V3 – V4 | 296.07 | 0.92 |
| V5 – V6 | 296.07 | 1.28 |
| V7 – V8 | 296.07 | 1.65 |
| V9 – V10 | 259.90 | 2.11 |
| V11 – V12 | 224.00 | 3.86 |
| V13 – V14 | 192.18 | 6.06 |
| V15 – V16 | 163.51 | 7.17 |
| V17 – V18 | 163.51 | 8.12 |
| V19 – V20 | 113.36 | 8.94 |
| V21 – V22 | 81.86 | 9.31 (9 min 18.6 sec) |

*Heuristic Block Size of 4: (Refer to Appendix C, Figure 20.)*

| Vehicle Group | Unmet Demand | Cumulative Time (min) |
|---|---|---|
| V1 – V4 | 296.08 | 1.33 |
| V5 – V8 | 276.10 | 3.32 |
| V9 – V12 | 231.38 | 11.42 |
| V13 – V16 | 168.38 | 17.51 |
| V17 – V20 | 104.82 | 114.44 |
| V21 – V22 | 73.32 | 115.51 (1 hr 55 min 30.89 sec) |

*Exact Method (22 vehicles at once through the model):*

| Unmet Demand | Cumulative Time (min) | Absolute Gap | Lower Bound |
|---|---|---|---|
| 61.45 | 246.12 | 33.89 | 27.56 |
| | (4 hrs 6 min 7.46 sec) | | |
| | Stopped after 10 hours without further improvement. | | |

**Scenario B**

Total Original Demand: 152.42 STONS

*Heuristic Block Size of 2: (Refer to Appendix C, Figure 21.)*

| Vehicle Group | Unmet Demand | Cumulative Time (min) |
|---|---|---|
| V1 – V2 | 150.14 | 0.37 |
| V3 – V4 | 145.34 | 0.98 |
| V5 – V6 | 137.19 | 1.38 |
| V7 – V8 | 129.04 | 1.73 |
| V9 – V10 | 96.50 | 3.90 |
| V11 – V12 | 65.20 | 5.16 |
| V13 – V14 | 36.83 | 9.67 |
| V15 – V16 | 19.04 | 11.07 |
| V17 – V18 | 7.00 | 11.48 |
| V19 – V20 | 1.58 | 12.54 |
| V21 – V22 | 0.44 | 13.54 (13 min 32.54 sec) |

*Heuristic Block Size of 4: (Refer to Appendix C, Figure 22.)*

| Vehicle Group | Unmet Demand | Cumulative Time (min) |
|---|---|---|
| V1 – V4 | 143.94 | 0.19 |
| V5 – V8 | 126.49 | 3.94 |
| V9 – V12 | 62.45 | 18.75 |
| V13 – V16 | 19.31 | 28.87 |
| V17 – V20 | 2.11 | 38.36 |
| V21 – V22 | 0.97 | 39.73 (41 min 24.93 sec) |

*Exact Method (22 vehicles at once through the model):*

| Unmet Demand | Cumulative Time (min) | Absolute Gap | Lower Bound |
|---|---|---|---|
| 2.87 | 245.31 | 2.87 | 0.00 |
| | (4 hrs 5 min 18.47 sec) | | |
| | Stopped after 10 hours without further improvement. | | |

**Scenario C**

Total Original Demand: 143.85 STONS

*Heuristic Block Size of 2: (Refer to Appendix C, Figure 23.)*

| Vehicle Group | Unmet Demand | Cumulative Time (min) |
|---|---|---|
| V1 – V2 | 141.48 | 0.31 |
| V3 – V4 | 135.84 | 0.92 |
| V5 – V6 | 125.84 | 1.30 |
| V7 – V8 | 118.79 | 2.25 |
| V9 – V10 | 86.29 | 6.98 |
| V11 – V12 | 57.54 | 13.76 |
| V13 – V14 | 34.64 | 21.99 |
| V15 – V16 | 15.54 | 23.49 |
| V17 – V18 | 4.83 | 24.04 |
| V19 – V20 | 0.00 | 24.27 |
| V21 – V22 | 0.00 | 24.29 (24 min 17.4 sec) |

*Heuristic Block Size of 4: (Refer to Appendix C, Figure 24.)*

| Vehicle Group | Unmet Demand | Cumulative Time (min) |
|---|---|---|
| V1 – V4 | 135.29 | 1.42 |
| V5 – V8 | 120.51 | 6.49 |
| V9 – V12 | 59.46 | 66.55 |
| V13 – V16 | 28.50 | 126.62 |
| V17 – V20 | 2.40 | 129.31 |
| V21 – V22 | 0.00 | 129.37 (2 hrs 9 min) |

*Exact Method (22 vehicles at once through the model):*

| Unmet Demand | Cumulative Time (min) | Absolute Gap | Lower Bound |
|---|---|---|---|
| 0.00 | 37.66 (37 min 39.73 sec) | 0.00 | 0.00 |

### c) *VRP Solution Analysis*

This model is different than any other model previously done for the Combat Service Support environment in that it aims at selecting near optimal routes depending upon demand priorities and vehicles available for transportation use. Everything as far as route selection has been manual before this model. Prior to this

model no models existed for Combat Service Support that involved optimization software in the selection of routes. The closest model in relationship to the one we developed is the Transportation Coordinators'-Automated Information for Movement System II (TC-AIMS II). TCAIMS allows transportation planners and coordinators to create, manage, and track vehicles (ATCL-T 1999). A route module is used in TCAIMS for the user to build routes, by designating nodes and legs. These routes are used as the basis for movement and are stored in reference tables. A user of TCAIMS would fill in the origin, destination, time, distance, and transportation constraints associated with each leg in a route and then select an appropriate route based upon this information. Our model does all of the above and selects an appropriate route in coordination with other existing resources of the system. TCAIMS is much more robust though in that it combines individual Service terminology and operating procedures into one standard multifaceted transportation system (ATCL-T 1999). Our model does not claim to accomplish all that TCAIMS accomplishes. Our VRP model takes the aspect of route selection and goes a step further by seeking a solution using optimization methods. As future versions of route selection models using optimization methods are developed for the Combat Service Support environment they could be interfaced with TCAIMS or some similar program. A route selected through an optimization method would be a valuable initial starting point for planners when faced with the task of using classical "manual planning" for selecting vehicle routes.

In all the scenarios modeled, the final objective function value using the heuristic with block size 2 is comparable to all other solutions and takes substantially less time to solve the problem. What the model sacrifices in unmet demand it makes up for in the speed to solve the problem. An end user may use the results from the heuristic block size 2 as a critical first step in a planning process for solving complex tasks of routing vehicles. In both cases of large demand, scenarios A and B, the problem was solved in less than 14 minutes. Without a heuristic, the model took upwards of 4 hours to solve. In scenario B, the heuristic block size 2 was the best solution overall although the exact method terminates with an insignificant quantity of STONS of unmet demand (satisfying the tolerance criterion). The same logic goes for scenario C. The heuristic using block size 2 solved the problem in the shortest time frame. A difference between scenario C and

the other scenarios is that the problem was solved to the point of zero unmet demand. This leaves no requirement for external support in meeting all the re-supply needs, although in case B the unmet demand is almost negligible when compared with the total demand.

All other statistics regarding actions of the vehicles as they travel through a suggested route are discussed in the exploratory analysis located in Chapter V.

THIS PAGE INTENTIONALLY LEFT BLANK

# V. ANALYSIS OF THE VRP & SIMULATION MODELS

As discussed in Chapter IV, the VRP is a deterministic model. All the data are assumed to be known with certainty. Unfortunately, in the real problem some parameters are subject to change due to random events during the course of the deployment. For these parameters, the VRP was solved replacing the random data by average and/or conservative values. In this section we analyze the validity of the solution provided by the VRP model by comparing that solution with the three simulated scenarios under the three different conditions for each alternative. In addition, the simulation incorporates other features that were omitted in the VRP model, such as loading and enroute waiting times, as well as a more detailed physical network.

## A. MEASURES OF EFFECTIVENESS

Measures of Effectiveness (MOEs) must be quantifiable, so that assessments can be objectively base-lined and tracked. The MOEs should be appropriate for tactical operational effectiveness. MOEs chosen in this model are the typical measures used in Combat Service Support operations to evaluate effectiveness (Edwards 1993). The MOEs used in this analysis are listed below:

"Do all vehicles make their deliveries within the appropriate time windows? What is the mean arrival time to the time windows? What is the percent of vehicles that are early and how early are they? How many vehicles are early? The same MOEs are asked of vehicles that are late. What is the average delay time incurred while enroute? What is the tonnage hauled during the operational period (ton-miles)? What is the percent of demand that is satisfied? Do all vehicles make their deliveries within the appropriate time windows?"

## B. EXPLORATORY ANALYSIS

A $2^{4-1}$ half-fraction Resolution IV design was established as a tool for conducting the exploratory analysis on the data (Box, Hunter, Hunter 1978). The main MOE that was the focal point of the exploratory analysis was the mean arrival times at the demand

points. The four factors that were used and how they were varied are summarized as follows.

| | Variable | +1 | -1 |
|---|---|---|---|
| **A** | *Speed (kph)*: | 15 | 35 |
| **B** | *Load times*: | Triangle Distribution | Optimistic Loading Times |
| **C** | *Delays in load*: | probability of 50% | probability of 0% |
| **D** | *Wait enroute*: | Gamma Distribution | Fixed according to VRP |

Speed was either 15 or 35 kilometers per hour. Loading times were either random having a triangle distribution, or deterministic using optimistic loading times. Possible delays in loading were modeled as having either a 50% probability of being delayed versus a 0% probability of delay. Wait times while enroute either followed the Gamma distribution or were held at the fixed times that the VRP model dictated.

The order of the runs was randomized. The same type of design was accomplished for every scenario. This included a $2^{4-1}$ half-fraction Resolution IV design for each heuristic block size as well as a $2^{4-1}$ design for the exact method. The order of collecting data for each design was also randomized. The standard design may be referred to in Figure 8 . The order of every run for all the designs may be viewed in Appendix E.

| FACTOR | | | |
|---|---|---|---|
| A | B | C | D |
| -1 | -1 | -1 | -1 |
| +1 | -1 | -1 | +1 |
| -1 | +1 | -1 | +1 |
| +1 | +1 | -1 | -1 |
| -1 | -1 | +1 | +1 |
| +1 | -1 | +1 | -1 |
| -1 | +1 | +1 | -1 |
| +1 | +1 | +1 | +1 |

***Figure 8. $2^{4-1}$ Half Fraction Resolution IV Design (From: Box, Hunter, Hunter 1978)***
*Standard order of a $2^{4-1}$ Resolution IV Design used for the exploratory analysis in this thesis.*

The mean arrival times used for the analysis were obtained through the use of batch means. The model was run through multiple replications simulating thousands of

vehicles making deliveries along a designated route. Correlograms were then plotted for each set of the data looking at the autocorrelation function versus the lag (refer to Figure 9).

Using this plot, it is desired to find where correlation drops below 0.1. A truncation point was determined by multiplying the lag point where correlation drops below 0.1 by 4 (Law & Kelton 2000). All the data prior to the truncation point is thrown out since it is considered to be biased. A second autocorrelation function was then plotted with the remaining data to determine if it was similar to the first set of data. If it was similar then batches were created from this remaining data to find the batch mean. The size of each batch was equal to the truncation point. If the truncation point was not similar to the first set of data then the procedure was repeated once again. This same procedure was conducted to find the batch means for every run of the simulation along with their 95% confidence intervals in support of the factorial design.

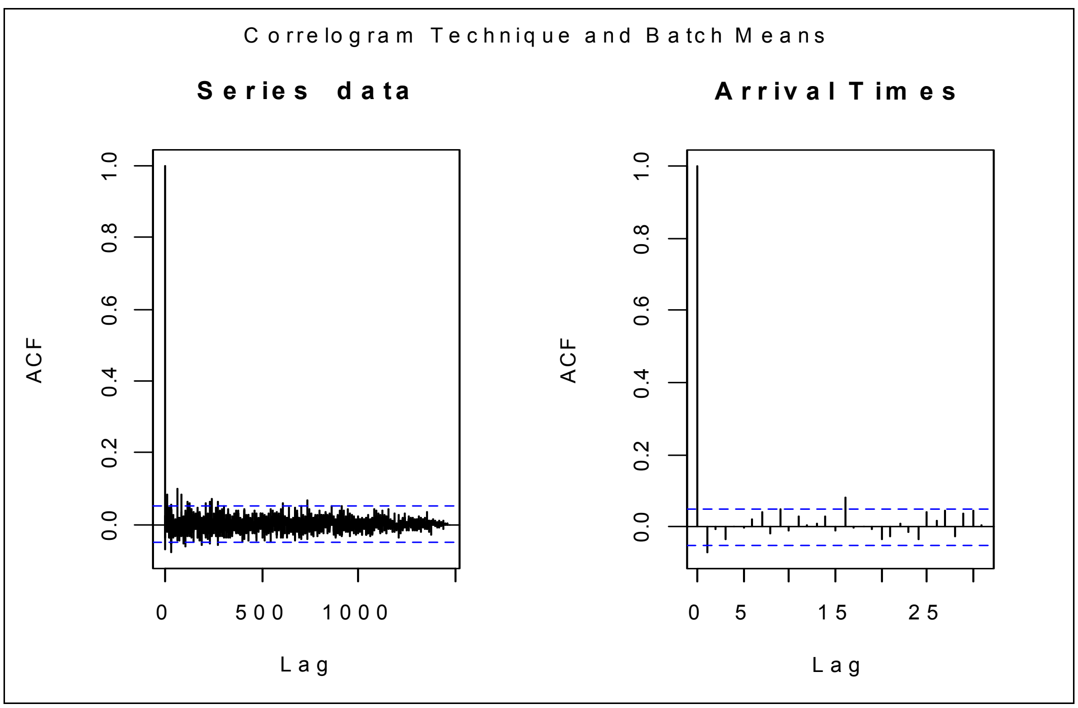


***Figure 9. Typical Correlogram of Arrival Times***

*Correlogram of the arrival times for Scenario A (Heuristic batch size 2). The plot on the left is every data point. The plot on the right shows the means of the batches and that the system has indeed stabilized or reached a steady state. Hence, correlation was negligible.*

A summary table of all results of the simulation and of the batch means may be viewed in Appendix E.

The first step in the analysis was to test the assumptions of the data. Refer to Figures 10 and 11 for the normal probability plot of the residuals and the residuals versus the fitted values. Figure 10 shows that the residuals are relatively straight with respect to the normal line so the assumption of normality holds for the analytical test. Figure 11 indicates that there is common variance so the assumption of homoscedasticity is reasonable as well for the analytical test.

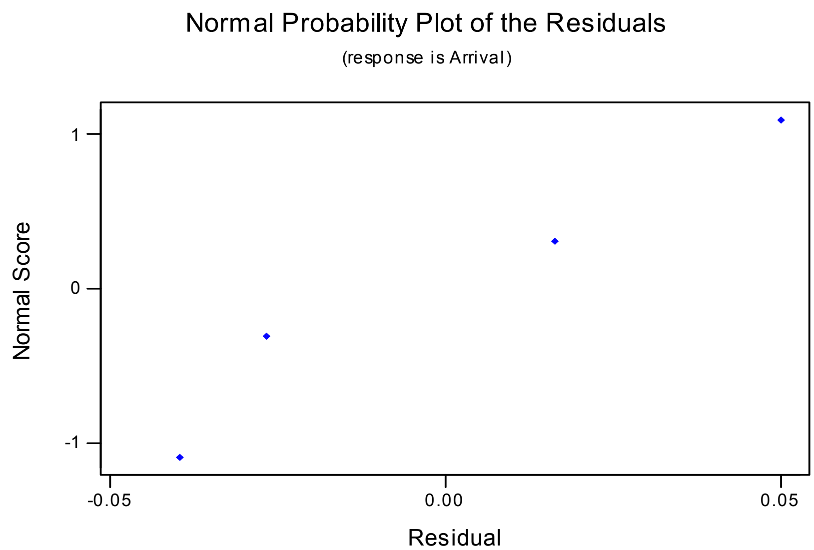


***Figure 10. Normal Plot of Effects***

*The assumption of normality holds since the data are relatively straight with respect to a normal line for Scenario A ( batch size 2).*

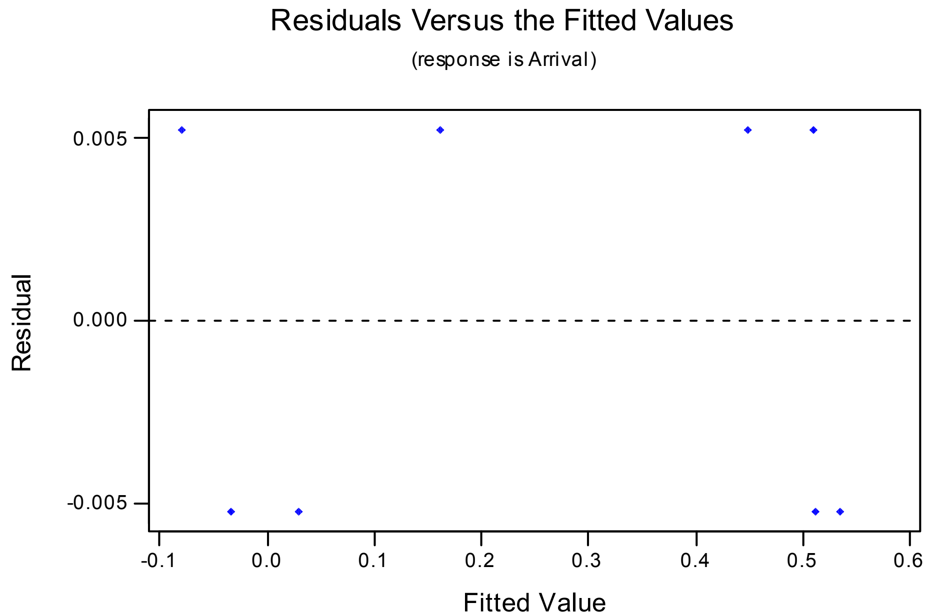


***Figure 11. Residuals versus fitted values***

*The assumption of homoscedasticity holds for Scenario A (Heuristic batch size 2).*

The assumptions held in a similar manner for all other scenarios. The analysis proceeded by looking at the Analysis of Variance (ANOVA) table for the main effects and what was deemed to be appropriate interactions. The ANOVA table indicated that varying speed of the vehicle has the most profound effect on the mean arrival time.

Analysis of Variance for Arrival, using Adjusted SS for Tests

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Speed | 1 | 0.466578 | 0.466578 | 0.466578 | 2116.00 | 0.014 |
| Load | 1 | 0.008712 | 0.008712 | 0.008712 | 39.51 | 0.100 |
| DelayLoad | 1 | 0.003872 | 0.003872 | 0.003872 | 17.56 | 0.149 |
| Wait | 1 | 0.014792 | 0.014792 | 0.014792 | 67.08 | 0.077 |
| Speed*Load | 1 | 0.001105 | 0.001105 | 0.001105 | 5.01 | 0.268 |
| Speed*Wait | 1 | 0.008845 | 0.008845 | 0.008845 | 40.11 | 0.100 |
| Error | 1 | 0.000220 | 0.000220 | 0.000220 | | |
| Total | 7 | 0.504123 | | | | |

This led to the main effects plot which shows that the speed of the vehicle has a drastic effect on the mean arrival time compared with the other three main effects (refer to Figure 12).

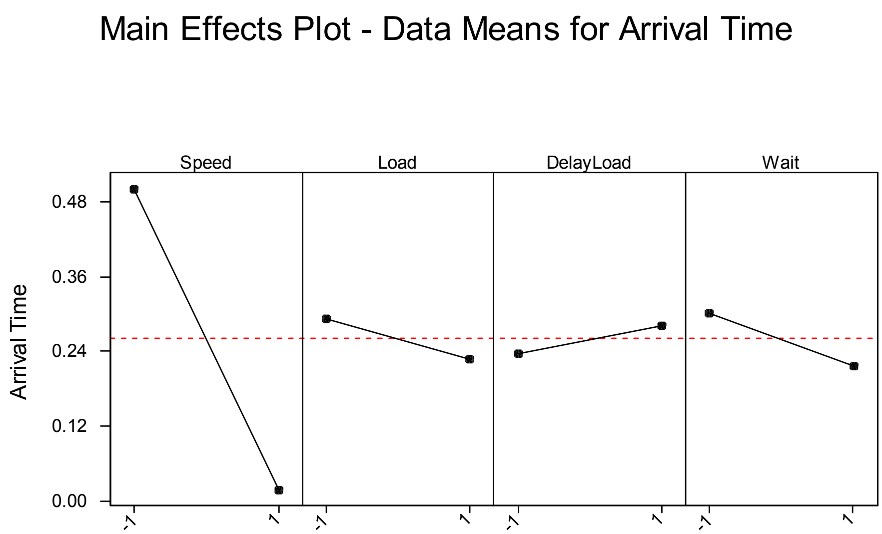


***Figure 12. Main Effects Plot (Response Variable of Arrival Time)***
*Graphical depiction of how drastically the speed of the vehicle effects the mean arrival time for Scenario A (heuristic size 2).*

The interactions plot may be referred to in Figure 13. Speed had the largest effect once again in all instances.

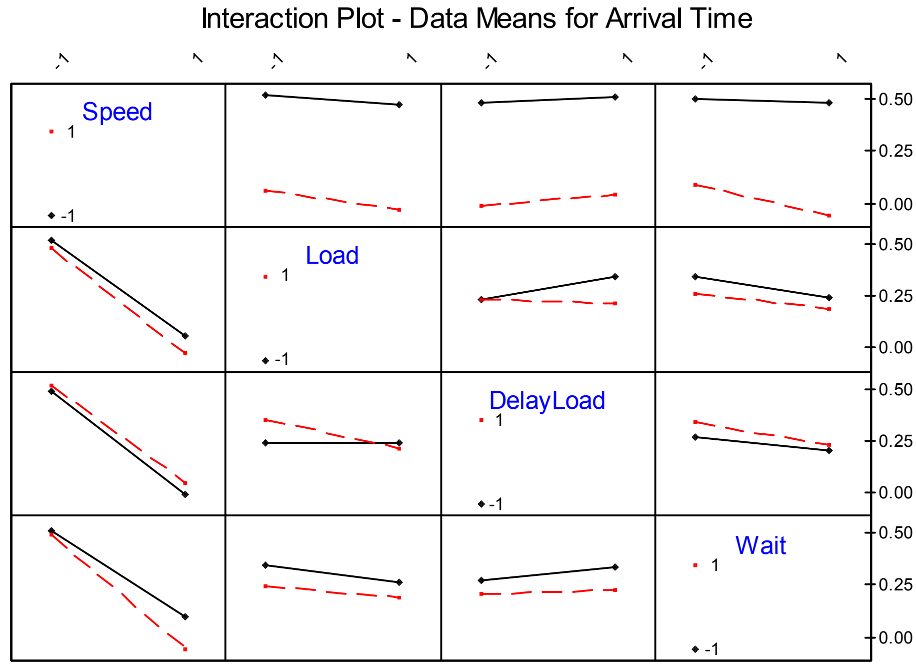


***Figure 13. Interactions Plot (Response Variable of Arrival Time)***
*This indicates how all the main effects and interactions effect the mean arrival time for Scenario A (heuristic size 2). The dashed line depicts when a factor is at the +1 state and the solid line is the –1 state. The lines are connecting the data means and show the trend the data takes when varied from the +1 to the –1 state.*

The interaction plot also seemed to indicate that there was no statistical difference in the main effects of loading, delay in loading, and waiting enroute in how they were varied for this analysis. A quick plot of the confidence interval plots (refer to Figures 14 through 17) revealed that there was almost zero difference between varying these three factors. Speed was the only factor that was varied enough to have a significant effect on changing the response variable of the arrival time.

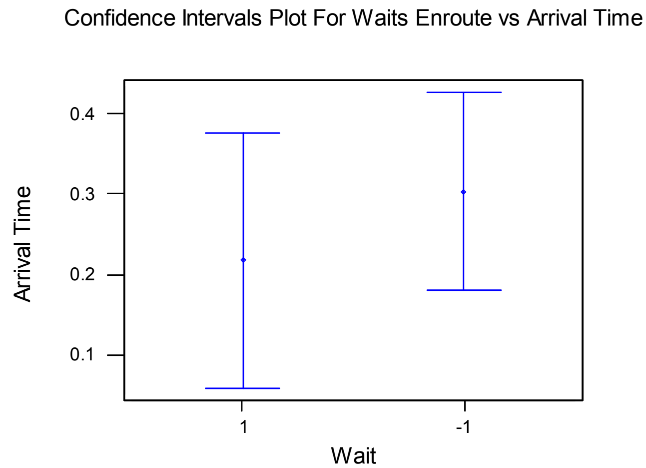


***Figure 14. Confidence Interval Plot for Waiting Enroute***

*This shows that no significant statistical difference exists in how the wait times were varied for this analysis.*

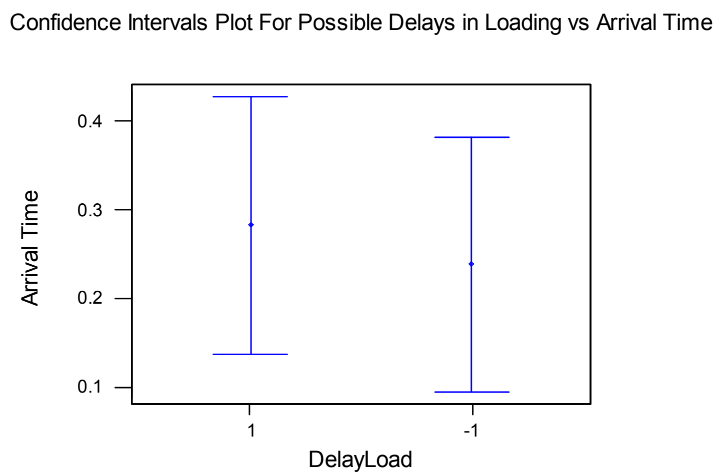


***Figure 15. Confidence Interval Plot for Possible Delays in Loading***

*This shows that no significant statistical difference exists in how the possible delays in loading were varied for this analysis. Both factors are almost identical from a statistical sense.*

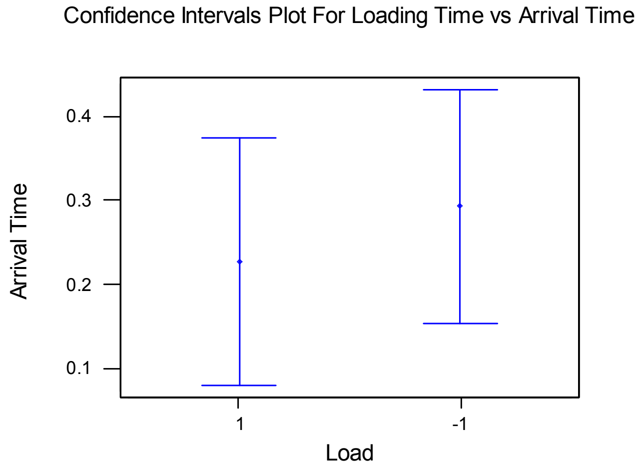


***Figure 16. Confidence Interval Plot for LoadingTimes***

*This shows that no significant statistical difference exists in how the loading times were varied for this analysis. Both factors are almost identical from a statistical sense.*

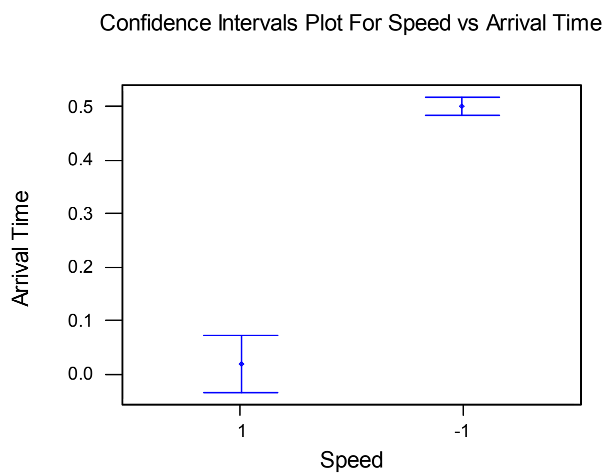


***Figure 17. Confidence Interval Plot for Vehicle Speed***

*This shows that significant statistical difference existed in how the speeds of the vehicles were varied for this analysis. The vehicles going 15 kph right around 0.0 indicating that they are always within the exact time window. The vehicles going 35 kph are always early. This complements the VRP model exactly.*

All of the above analysis was performed for every scenario in addition to Scenario A heuristic block size 2. The results were nearly identical for the remaining 8 designs.

No significant difference existed for the factors of loading, delay in loading, or the waiting along a route. There was a statistically significant difference in the factor of vehicular speed on the mean arrival time.

Significant results were also revealed in the other MOEs. There are very few times when the batch means revealed that the deliveries were made late. In all the cases where a late delivery was made it was an insignificant amount of time. Eighteen out of twenty-one of the late arrival times involved the vehicles traveling at its slowest speeds. This is noteworthy because the VRP model took a conservative approach and used a fixed speed of 15 kilometers per hour for every vehicle. The VRP also assumed that all vehicles were loaded prior to starting whereas the simulation explicitly modeled the loading operation. This may explain why a few vehicles are tardy when the route is simulated.

The VRP claims that all vehicles would arrive within the time windows. The simulation shows that vehicles arrive within the time windows most of the time. If the vehicles make their delivery within a time window then it is considered to be a success. Arriving early to a demand zone is considered a success unless the cargo could be considered 'vulnerable' for an attack at the waiting site. This is because the vehicles would still get their intended supplies to the unit on time. The VRP also allots for early arrivals by directing vehicles to wait at designated nodes until a delivery time window is reached. Viewing the arrival times and their corresponding 95% confidence intervals obtained from the simulation indicates that all deliveries make it to their intended place in a timely and efficient manner in all three scenarios for a majority of the time.

# VI. RECOMMENDATIONS AND CONCLUSIONS

## A. FINDINGS AND CONCLUSIONS

This thesis has provided the first crucial step in the analysis of the Logistics Operations Command and Control Capability (LOCCC) concept as developed by Colonel Grelson, 1st BSSG Commanding Officer, and demonstrates the immediate need for continued analysis in the area of Combat Service Support Operations and the LOCCC concept.

The study's specific results hold only for scenarios with a similar size of deployed forces, and a similar CSSE organization. The scenarios analyzed by this study consisted of a notional MEB sized force and a CSSE organized according to the LOCCC concept. This concept indicates the use of a centralized command and control and the use of one large MCSSD in GS for supporting all requisition needs. The LOCCC concept also entails dispatching vehicles to areas of need as they are required. Prior studies have involved strictly aircraft and the effects of aircraft on support.

Based upon the output of the Vehicle Routing Problem and the simulation, the concept modeled shows that in similar scenarios a CSSE would be able to provide a majority of the requisition needs in an efficient manner when tasked with supporting a MEB. If 100% support is required then this model spells out the need for incorporating aircraft into the scenario, supplying more vehicles to the CSSE, or providing some other transportation asset to the CSSE for logistical use. However, if the CSSE were tasked with supporting a smaller sized force such as a Task Force then additional assets would not be required. A CSSE with a similar structure and organization as the one modeled would have the capability to provide support needed with the vehicular assets that are available for its use.

Generally, the results show that when given exact time windows in which support needs to be provided, the factor of vehicular speed has the most significant effect on making a time window of the factors analyzed in this thesis. The time to load, the total delays in loading, as well as delays along a designated route to provide support are not

statistically significant as they are currently varied in this thesis when they are compared to the speed of the vehicle.

Finally, this model may be used in a very important way as a basis for future studies taken in the analysis of the LOCCC concept. This thesis is the breakthrough study in the sense that besides the time windows requirements in the vehicle routing problem, our VRP has special features such as vehicle capacity for each commodity and cargo incompatibility (e.g. fuel and ammunition) which has not been accomplished before in this field of study.

## B. RECOMMENDATIONS FOR FUTURE RESEARCH

The model developed for this thesis is a significant step in what should become a continuing study on Combat Service Support (CSS) Operations and the concepts utilized to employ them. The focus of this thesis was to develop a working model as a tool to analyze concepts used in Combat Service Support Operations, and an initial model was developed. More detailed analysis and model formulation will assist in the ongoing development of new CSS concepts. The following are just a few areas in which this work may be expanded for future research:

- ❖ As the optimization model stands, it is too slow to be of any operational use. A more robust heuristic for use in the optimization portion of the model must be developed in order to solve the optimization program to optimality or near optimality in a timelier manner. It is suggested to obtain an initial solution and further refine that solution by adapting local search based strategies (Savelsberg 1985 & Solomon 1987). An alternative method for developing a better heuristic would be to split up the road network into various avenues of approach or to look at vehicles according to different grouping criteria.
- ❖ A heuristic may also be developed directly within the simulation using Konig. Konig is a software component for graphs and networks developed by Jack Jackson as part of his dissertation research at the Naval Postgraduate School in Monterey, California. This approach would

enhance the simulation portion of the model. The road network XML file used within this simulation was developed to be used directly with Konig.

- GAMS/CPLEX, although extremely powerful are not widely available. It was chosen for its computational prowess and was beneficial for this thesis. However, in the future it would be beneficial as well to develop an optimization model within Java. The Java Virtual Machine can operate on multiple operating systems and is available for download from Sun Microsystems' World Wide Web site, www.sun.com, for no cost. This would make the model more widely available to whoever desires to work on any extension of the model.
- Obtain data from an actual operation that took place and run the scenario through the model in order to compare and contrast actual results to the model.
- Upon developing a more robust heuristic for solving the Vehicle Routing Problem with Time Windows, more nodes may be added into the road network. This would allow the optimization model to more closely resemble the real network used in a simulation model.
- Model the dynamic nature of the delivery points as the pace of offensive operations moves forward and build upon the current simulation. Factors may be found in MSTP Pamphlet 5-0.3.
- Add on to the model allowing for crew operating capabilities/rest, scheduled equipment maintenance and other operational constraints.
- Expand the model to include specific Marine Corps Ammunition Items by DOD Identification Code (DODIC). The current model accounts only for raw tonnage. It does not take into account the different categories of ammunition that may or may not be transported together.
- Expand upon the current analytical model in this thesis and develop a decision support system.
- The use of air transportation should also be incorporated into the model in order to add more realism to the model.

- ❖ Expand upon the penalty function for unmet demand in the optimization model.
- ❖ Model additional sustainment requirements so that the model will span a wider range of needs (Types I – X) .
- ❖ Continue a deeper exploratory analysis varying more factors to a more significant level.
- ❖ Integrate the VRP model as a part of the simulation so that the VRP can be dynamically reoptimized as the simulation progresses.

The Marine Corps should continue to develop improved models for the Combat Service Support environment. This would give a better evaluation for new schemes of maneuver and help to optimize the use of resources, assets, and network routes. A system is needed that is more versatile, deployable, and expandable. Former distribution concepts developed to support the conflict mold of WWII and the Cold War are now inadequate and require the development of a number of improvements. Building the proper simulation model and optimization models will help in this area to bring the proper concepts into fruition.

# APPENDIX A.  ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AAV | Assault Amphibious Vehicle |
| AOA | Area of Operations |
| AOR | Area of Responsibility |
| BSSG | Brigade Service Support Group |
| CEB | Combat Engineer Battalion |
| CPU | Central Processing Unit |
| CSSD | Combat Service Support Detachment |
| CSSE | Combat Service Support Element |
| C2 | Command and Control |
| DODIC | Department of Defense Identification Code |
| DOM | Document Object Model |
| DOS | Days of Supply |
| DS CSSE’s | Direct Support CSSE |
| EMW | Expeditionary Maneuver Warfare |
| FSSG | Force Service Support Group |
| FMCC | Force Movement Control Center |
| gal | Gallon |
| GAMS | General Algebraic Modeling System |
| GCE | Ground Combat Element |
| gph | gallons per hour |
| GS CSSE | General Support CSSE |
| LAR | Light Armored Vehicle |
| LMCC | Logistics Movement Control Center |
| LOCCC | Logistics Operations Command and Control Capability |
| LOTS | Logistics Over-the-shore |
| LVS | Logistics Vehicle System |
| MAGTF | Marine Air Ground Task Force |
| MarDiv | Marine Division |
| MARFOR | Marine Forces |
| MAW | Marine Aircraft Wing |
| MCAGCC | Marine Corps Air Ground Combat Center |
| MCO | Marine Corps Order |
| MCWP | Marine Corps Warfighting Publication |
| MCSSD | Mobile CSSD |
| MEB | Marine Expeditionary Brigade |
| MEF | Marine Expeditionary Force |
| MILSTAMP | Military Standard Transportation and Movement Procedures |
| MIP | Mixed Integer Program |
| MLC | MARFOR Logistics Command |
| MOE | Measure of Effectiveness |
| MORS | Military Operations Research Society |
| MRE | Meal Ready To Eat |

| | |
|---|---|
| MSR | Main Supply Route |
| MSTP | MAGTF Staff Training Program |
| OMFTS | Operational Maneuver from the Sea |
| RTF | Regimental Task Force |
| POL | Petroleum, Oil, and Lubricant |
| TC-AIMS II | Transportation Coordinators'-Automated Information for Movement Systems II |
| VRP | Vehicle Routing Problem |
| XML | Extensible Markup Language |

## APPENDIX B. DATA EMPLOYED IN THE MODEL

### A. SUPPLY CLASS REQUIREMENTS

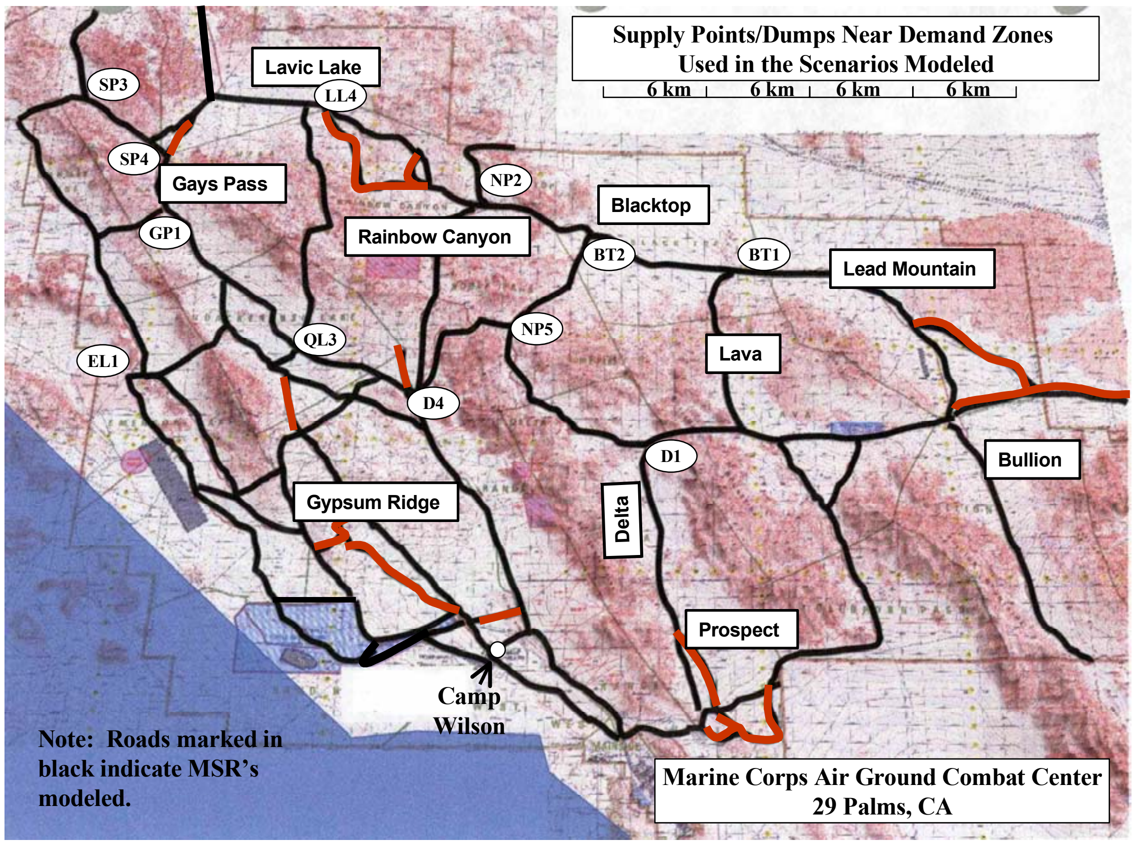


*Figure 18. Location of Supply Points Near Demand Zones (From: Parker 2000)*
*The circles depict the location of supply points/dumps near the demand zones that are modeled in this thesis.*

All of the tables used in this section have been derived from LOG2000. LOG2000 is a spreadsheet developed by Major Neita Armstrong and currently used by the 1st FSSG as one of the planning tools for calculating preliminary sustainment estimates. Class I requirements are derived from MSTP Pamphlet 5-0.3 and FM 101-10-1/2. Class III is based upon CNA study from April 2000. Class V is based upon MCO 8010.1E.

The requirements shown here are broken down by total requirements for the Ground Combat Element (GCE) and then by individual requirements for each of the

supported units comprising the GCE. The requirements are further broken down according to the vicinity of the demand zone for each of the supported units in the scenario. This includes the time windows corresponding to each of the requirements denoting when the units must receive supplies prior to transitioning to a different position. The time windows indicate an operating hour so if a unit demands a re-supply between 5 and 7.5 this indicates that the unit needs supplies between the $5^{th}$ and $7.5^{th}$ simulated hour of the simulation model.

### 1. Requirements for Scenario A

**Units to be Supported:**

| **UNITS** | # | PAX | | # | PAX | | # | PAX |
|---|---|---|---|---|---|---|---|---|
| INF CO (3) | 9.0 | 1638 | AAV CO (3) | 3.0 | 588 | LAR CO (3) | 1.0 | 139 |
| INF HQ/WPNS | 3.0 | 1278 | AAV HQCO | 0.7 | 368 | LAR HQCO | 0.0 | 0 |
| INF REGT HQ | 1.0 | 214 | ENGR CO (4) | 1.0 | 114 | **DIV HQ** | | |
| ARTY BTRY (3) | 3.0 | 441 | ENGR HQ | 0.7 | 281 | TRUCK CO | 0.0 | 0 |
| ARTY BN HQ | 0.7 | 139 | TANK CO (4) | 3.0 | 258 | OTHER | 0.0 | 0 |
| ARTY REGT HQ | 0.0 | 0 | TANK HQCO | 0.7 | 346 | HQCO | 0.0 | 0 |
| | | | | | | | | |
| **GCE TOTAL** | | **5804** | | | | | | |

**Supporting units**:

The supporting units were modeled to work from one location in accordance with the LOCCC concept as is explained in the thesis.

| **UNITS** | # | PAX | | # | PAX | | # | PAX |
|---|---|---|---|---|---|---|---|---|
| **CSSE** | | | | | | | | |
| **CSSD-1** | 0.0 | 0 | MCSSD-D | 1.0 | 284 | **CSSD-3** | 0.0 | 0 |
| **CSSD-2** | 0.0 | 0 | MCSSD-2X | 0.0 | 0 | MCSSD-3X | 0.0 | 0 |
| MCSSD-A | 1.0 | 294 | NBC | 0.0 | 0 | **CSSD-4** | 0.0 | 0 |
| MCSSD-B | 0.0 | 0 | EOD (# Teams) | 0.0 | 0 | **FSSG CE** | 0.0 | 0 |
| MCSSD-C | 0.0 | 0 | | | | | | |
| | | | | | | MSSG | 0.0 | 0 |
| | | | | | | **CSSD-5** | 0.0 | 0 |
| **CSSE TOTAL** | | **578** | **Amphib CSSD Total** | 0 | | **CSSD-6** | 0.0 | 0 |

TOTAL SUPPLY CLASS REQUIREMENT

| NO. DAYS | 1 | | | GCE TOTAL | CSSE TOTAL | FORCE TOTAL |
|---|---|---|---|---|---|---|
| **PERSONNEL** | | | | 5,804 | 578 | 6,382 |
| | | | | | | |
| **SUPPLY CLASS** | **FACTOR (LBS)** | | | | | |
| | **GCE** | **OTHER** | | | | |
| I (subsistence) | 5.580 | 5.580 | | 6.44 | 1.61 | 8.05 |
| V (ammunition) | | | | 35.57 | 0.17 | 35.74 |
| TOTAL (S/T) | | | | 42.01 | 1.78 | 43.79 |
| | | | | | | |
| **WATER (Class I (w))** | | | | | | |
| TEMPERATE CLIMATE | 3.800 | 3.800 | | 10,974.40 | 2,196.40 | 13170.8 |
| TOTAL WATER (GALS) | | | | 10,974.40 | 2,196.40 | 13170.8 |
| TOTAL WATER (S/T) | 8.5 | | | 46.64 | 9.33 | 55.97 |
| | | | | | | |
| **FUEL JP8 (Class III)** | | | | | | |
| FUEL FACTOR PER PERSON | 0.12 | | | 696.48 | 69.36 | 765.84 |
| GROUND EQUIPMENT | | | | 61,071.27 | 20,084.40 | 81155.67 |
| TOTAL GROUND FUEL (GAL) | | | | 61,767.75 | 20,153.76 | 81921.51 |
| TOTAL GROUND FUEL (ST) | 7 | | | 216.19 | 70.54 | 286.73 |

INDIVIDUAL SUPPLY CLASS REQUIREMENTS

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **9** | **3** | **1** | | **3** | **0.7** | | **3** | **0.7** | |
| **NO. DAYS** | **1** | INF **CO** | INF **HQ/WPNS** | INF **REGT HQ** | TOTAL **INF** | ARTY **BTRY** | ARTY **BN HQ** | TOTAL **ARTY** | AAV **CO** | AAV **HQCO** | TOTAL **AAV BN** |
| **PERSONNEL** | | **1,638** | **1,278** | **214** | **3,130** | **441** | **139** | **580** | **588** | **368** | **956** |
| | | | | | | | | | | | |
| **SUPPLY CLASS** | **FACTOR (LBS)** | | | | | | | | | | |
| | **GCE** | | | | | | | | | | |
| **I** | **5.580** | 4.57 | 3.57 | 0.60 | 0.60 | 1.23 | 0.39 | | 1.64 | 1.03 | 2.67 |
| **V** | | 1.84 | 2.49 | 0.56 | 4.89 | 17.33 | 0.10 | 17.44 | 1.66 | 5.30 | 6.96 |
| **TOTAL** | | **6.41** | **6.05** | **1.16** | **5.49** | **18.56** | **0.49** | **17.44** | **3.30** | **6.33** | **9.63** |
| | | | | | | | | | | | |
| **WATER** | | | | | | | | | | | |
| **TEMPERATE CLIMATE** | **3.800** | 6,224 | 4,856 | 813 | 11,894 | 1,676 | 529 | 2,205 | 2,234 | 1,397 | 3,631 |
| **TOTAL WATER (GALS)** | | **6,224** | **4,856** | **813** | **11,894** | **1,676** | **529** | **2,205** | **2,234** | **1,397** | **3,631** |
| **TOTAL WATER (S/T)** | **8.5** | **26.45** | **20.64** | **3.46** | **50.55** | **7.12** | **2.25** | **9.37** | **9.50** | **5.94** | **15.43** |
| | | | | | | | | | | | |
| **FUEL JP8** | | | | | | | | | | | |
| **PERSONNEL** | **0.12** | **197** | **153** | **26** | **376** | **53** | **17** | **70** | **71** | **44** | **115** |
| **GROUND EQUIPMENT** | | | **2,310** | **1,913** | **4,223** | **10,061** | **1,867** | **11,928** | **14,837** | **4,731** | **19,568** |
| **Total Ground Fuel (Gal)** | | **197** | **2,463** | **1,939** | **4,599** | **10,113** | **1,884** | **11,998** | **14,908** | **4,775** | **19,683** |
| **Total Ground Fuel (ST)** | **7** | **0.69** | **8.62** | **6.79** | **16.10** | **35.40** | **6.59** | **41.99** | **52.18** | **16.71** | **68.89** |
| | | | | | | | | | | | |

(CONTINUATION) INDIVIDUAL SUPPLY CLASS REQUIREMENTS

| | | 1 | 0.7 | | 3 | 0.7 | | 1 | |
|---|---|---|---|---|---|---|---|---|---|
| **NO. DAYS** | **1** | ENGR **CO** | ENGR **HQ/SUPT** | TOTAL **ENGR BN** | TANK **CO** | TANK **HQCO** | TOTAL **TANKS** | LAR **CO** | TOTAL **LAR BN** |
| **PERSONNEL** | | **114** | **281** | **395** | **258** | **346** | **604** | **139** | **139** |
| | | | | | | | | | |
| **SUPPLY CLASS** | **FACTOR (LBS)** | | | | | | | | |
| | **GCE** | | | | | | | | |
| **I** | **5.580** | 0.32 | 0.79 | 1.10 | 0.72 | 0.96 | 1.68 | 0.39 | 0.39 |
| **V** | | 2.28 | 0.70 | 2.98 | 1.52 | 0.56 | 2.08 | 1.22 | 1.22 |
| **TOTAL** | | **2.60** | **1.48** | **4.08** | **2.24** | **1.53** | **3.77** | **1.61** | 1.61 |
| | | | | | | | | | |
| **WATER** | | | | | | | | | |
| **TEMPERATE CLIMATE** | **3.800** | 433 | 1,069 | 1,503 | 980 | 1,314 | 2,294 | 528 | 528 |
| **TOTAL WATER (GALS)** | | **433** | **1,069** | **1,503** | **980** | **1,314** | **2,294** | **528** | 528 |
| **TOTAL WATER (S/T)** | **8.5** | **1.84** | **4.54** | **6.39** | **4.17** | | **9.75** | **2.24** | 2.24 |
| | | | | | | | | | |
| **FUEL JP8** | | | | | | | | | |
| **PERSONNEL** | **0.12** | **14** | **34** | **47** | **31** | **41** | **72** | **17** | 17 |
| **GROUND EQUIPMENT** | | **204** | **7,192** | **7,396** | **13,534** | **3,221** | **16,755** | **1,201** | 1,201 |
| **Total Ground Fuel (Gal)** | | **218** | **7,226** | **7,444** | **13,565** | **3,262** | **16,827** | **1,218** | 1,218 |
| **Total Ground Fuel (ST)** | **7** | **0.76** | **25.29** | **26.05** | **47.48** | **11.42** | **58.90** | **4.26** | 4.26 |
| | | | | | | | | | |

## **Vehicles Available for Lift Support**:

The number of vehicles available for use transporting sustainment requirements is notional. The purpose of the model is to analyze operating concepts not to find the optimal composition of vehicles to use. The model will utilize the available LVS', 5 Tons, and HMMWVs to fulfill the lift requirements.

Vehicles available for use by the CSSE and MCSSDs were derived by the author through the use of Exercise Desert Knight / Steel Knight 2001, Commanding Officer Confirmation Brief dated November 16, 2000.

| | CSSE |
|---|---|
| | |
| PWR UNIT, FRNT, 12 1/2 TON, LVS | 14 |
| TRUCK, CARGO, 5 TON | 5 |
| TRUCK UTIL, 1.25 TON, HMMWV | 2 |
| | |

Unit locations are based upon the author's interpretation and are solely for analyzing the LOCCC concept. A notional Marine Expeditionary Brigade sized force was use with the main element requiring support being a Regimental Combat Team. As far as specific locations on the ground at 29 Palms are concerned, a scenario was chosen with demand quantities and the author just proceeded counterclockwise (Prospect, Delta-T, Cleghorn Pass, Lead mountain, Black Top, Rainbow Canyon, Lavic Lake, Gays Pass, Quackenbush, Gypsum Ridge). Refer to Figure 8 for the actual locations specified in the summary of the demand zones listed in each of the scenarios below.

**Summary of Demand Zones for Scenario A:**

| | | | | Supply Class Requirements (ST) | | | |
|---|---|---|---|---|---|---|---|
| **Vicinity of Demand Zone** | **Units** | **#** | **PAX** | **I (c) - MRE** | **I (w) - water** | **III (w) - Fuel** | **V(w) - Ammo** |
| Sunshine Peak (SP3) | Inf Co | 3 | 546 | 0.00 | 0.00 | 0.23 | 0.61 |
| | | **Total:** | 546 | 0.00 | 0.00 | 0.23 | 0.61 |
| Sunshine Peak (SP4) | Inf HQ/Wpns | 2 | 852 | 0.00 | 0.00 | 5.75 | 1.66 |
| | | **Total:** | 852 | 0.00 | 0.00 | 5.75 | 1.66 |
| Lavic Lake (LL4) | Inf Co | 3 | 546 | 0.00 | 0.00 | 0.23 | 0.61 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Total:** | 546 | 0.00 | 0.00 | 0.23 | 0.61 |
| Gays Pass (GP1) | Arty Btry | 2 | 294 | 0.00 | 4.75 | 23.60 | 11.56 |
| | | **Total:** | 294 | 0.00 | 4.75 | 23.60 | 11.56 |
| Emerson Lake (EL1) | AAV Co | 3 | 588 | 1.64 | 9.50 | 52.18 | 1.66 |
| | AAV HQ Co | 1 | 368 | 1.03 | 5.94 | 16.71 | 5.30 |
| | | **Total:** | 956 | 2.67 | 15.44 | 68.89 | 6.96 |
| Noble Pass (NP2) | Inf HQ/Wpns | 1 | 426 | 0.00 | 0.00 | 2.87 | 0.83 |
| | | **Total:** | 426 | 0.00 | 0.00 | 2.87 | 0.83 |
| Black Top (BT2) | Inf Co | 3 | 546 | 0.00 | 0.00 | 0.23 | 0.61 |
| | | **Total:** | 546 | 0.00 | 0.00 | 0.23 | 0.61 |
| Noble Pass (NP5) | Arty Btry | 1 | 147 | 0.00 | 2.37 | 11.80 | 5.78 |
| | | **Total:** | 147 | 0.00 | 2.37 | 11.80 | 5.78 |
| Black Top (BT1) | Tank Co | 3 | 258 | 0.72 | 4.17 | 47.48 | 1.52 |
| | Tank HQ Co | 1 | 346 | 0.96 | 5.58 | 11.42 | 0.56 |
| | LAR Co | 1 | 139 | 0.39 | 2.24 | 4.26 | 1.22 |
| | | **Total:** | 743 | 2.07 | 11.99 | 63.16 | 3.30 |
| Delta (D4) | Engr Co | 1 | 114 | 0.32 | 1.84 | 0.76 | 2.28 |
| | Engr HQ | 1 | 281 | 0.79 | 4.54 | 25.29 | 0.70 |
| | Arty Bn HQ | 1 | 139 | 0.00 | 2.25 | 6.59 | 0.10 |
| | Inf Reg HQ | 1 | 214 | 0.60 | 3.46 | 6.79 | 0.56 |
| | | **Total:** | 748 | 1.71 | 12.09 | 39.43 | 3.64 |
| | | **Grand Total:** | 5804 | 6.45 | 46.64 | 216.19 | 35.56 |
| | | **Total Demand:** | 304.84 | STONS | | | |

**Time Window Requirements for the above demands based upon operating hours:**

| | Time Window (hours) | |
|---|---|---|
| Location | Early | Late |
| SP3 | 5.667 | 7.000 |
| SP4 | 5.000 | 6.333 |
| LL4 | 6.667 | 7.667 |
| GP1 | 7.000 | 8.333 |
| EL1 | 1.667 | 5.000 |
| NP2 | 5.333 | 6.333 |
| BT2 | 4.667 | 5.667 |
| NP5 | 3.333 | 4.333 |
| BT1 | 4.000 | 4.667 |
| D4 | 10.000 | 11.667 |

### 2. Requirements for Scenario B

The units to be supported and the supporting units were the same as in Scenario A. The supply requirements were just 50% of the requirement in Scenario A. Hence, it was

just a partial re-supply instead of a full re-supply as above. The vehicles available for lift support remained the same as did the time window restraints. The requirements are summarized below.

### Summary of Demand Zones for Scenario B:

| Vicinity of Demand Zone | Units | # | PAX | Supply Class Requirements (ST) I (c) - MRE | I (w) – water | III (w) - Fuel | V(w) - Ammo |
|---|---|---|---|---|---|---|---|
| Sunshine Peak (SP3) | Inf Co | 3 | 546 | 0.00 | 0.00 | 0.12 | 0.31 |
| | | **Total:** | 546 | 0.00 | 0.00 | 0.12 | 0.31 |
| Sunshine Peak (SP4) | Inf HQ/Wpns | 2 | 852 | 0.00 | 0.00 | 2.88 | 0.83 |
| | | **Total:** | 852 | 0.00 | 0.00 | 2.88 | 0.83 |
| Lavic Lake (LL4) | Inf Co | 3 | 546 | 0.00 | 0.00 | 0.12 | 0.31 |
| | | **Total:** | 546 | 0.00 | 0.00 | 0.12 | 0.31 |
| Gays Pass (GP1) | Arty Btry | 2 | 294 | 0.00 | 2.38 | 11.80 | 5.78 |
| | | **Total:** | 294 | 0.00 | 2.38 | 11.80 | 5.78 |
| Emerson Lake (EL1) | AAV Co | 3 | 588 | 0.82 | 4.75 | 26.09 | 0.83 |
| | AAV HQ Co | 1 | 368 | 0.52 | 2.97 | 8.36 | 2.65 |
| | | **Total:** | 956 | 1.34 | 7.72 | 34.45 | 3.48 |
| Noble Pass (NP2) | Inf HQ/Wpns | 1 | 426 | 0.00 | 0.00 | 1.44 | 0.42 |
| | | **Total:** | 426 | 0.00 | 0.00 | 1.44 | 0.42 |
| Black Top (BT2) | Inf Co | 3 | 546 | 0.00 | 0.00 | 0.12 | 0.31 |
| | | **Total:** | 546 | 0.00 | 0.00 | 0.12 | 0.31 |
| Noble Pass (NP5) | Arty Btry | 1 | 147 | 0.00 | 1.19 | 5.90 | 2.89 |
| | | **Total:** | 147 | 0.00 | 1.19 | 5.90 | 2.89 |
| Black Top (BT1) | Tank Co | 3 | 258 | 0.36 | 2.09 | 23.74 | 0.76 |
| | Tank HQ Co | 1 | 346 | 0.48 | 2.79 | 5.71 | 0.28 |
| | LAR Co | 1 | 139 | 0.20 | 1.12 | 2.13 | 0.61 |
| | | **Total:** | 743 | 1.04 | 6.00 | 31.58 | 1.65 |
| Delta (D4) | Engr Co | 1 | 114 | 0.16 | 0.92 | 0.38 | 1.14 |
| | Engr HQ | 1 | 281 | 0.40 | 2.27 | 12.65 | 0.35 |
| | Arty Bn HQ | 1 | 139 | 0.00 | 1.13 | 3.30 | 0.05 |
| | Inf Reg HQ | 1 | 214 | 0.30 | 1.73 | 3.40 | 0.28 |
| | | **Total:** | 748 | 0.86 | 6.05 | 19.72 | 1.82 |
| | | **Grand Total:** | 5804 | 3.23 | 23.32 | 108.095 | 17.78 |
| | | **Total Demand:** | 152.42 STONS | | | | |

**Time Window Requirements for the above demands based upon operating hours:**

| Location | Time Window (hours) Early | Late |
|---|---|---|
| SP3 | 5.667 | 7.000 |
| SP4 | 5.000 | 6.333 |
| LL4 | 6.667 | 7.667 |
| GP1 | 7.000 | 8.333 |
| EL1 | 1.667 | 5.000 |
| NP2 | 5.333 | 6.333 |
| BT2 | 4.667 | 5.667 |
| NP5 | 3.333 | 4.333 |
| BT1 | 4.000 | 4.667 |
| D4 | 10.000 | 11.667 |

### 3. Requirements for Scenario C

This third scenario represents a small task force demanding partial re-supply of certain commodities. The supporting units and the vehicles available for lift once again remained the same for this partial re-supply. The re-supply requirements and their corresponding time window constraints are summarized below.

| | Supply Class Requirements (ST) | | | |
|---|---|---|---|---|
| Vicinity of Demand Zone | I (c) - MRE | I (w) - water | III (w) - Fuel | V(w) - Ammo |
| Black Top (BT1) | 1.00 | 5.50 | 25.00 | 2.60 |
| Delta (D1) | 0.30 | 1.70 | 8.00 | 0.70 |
| Noble Pass (NP5) | 1.20 | 6.90 | 27.00 | 3.20 |
| Lavic Lake (LL4) | 0.40 | 2.20 | 10.00 | 1.00 |
| Gays Pass (GP1) | 0.50 | 2.60 | 13.00 | 1.20 |
| Quackenbush Lake (QL3) | 0.40 | 2.10 | 9.00 | 0.90 |
| Emerson Lake (EL1) | 0.50 | 2.70 | 13.00 | 1.25 |
| | 4.30 | 23.70 | 105.00 | 10.85 |

Total Demand: 143.85 STONS

**Time Window Requirements for the above demands based upon operating hours:**

| Location | Time Window (hours) Early | Late |
|---|---|---|
| BT1 | 3.333 | 5.333 |
| LL4 | 6.667 | 8.333 |
| D1 | 3.000 | 5.667 |

| | | |
|---|---|---|
| NP5 | 7.000 | 8.333 |
| QL3 | 10.000 | 10.667 |
| EL1 | 8.333 | 9.333 |
| GP1 | 7.000 | 9.000 |

## B. GENERIC FORMAT FOR VRP MAIN DATA IN GAMS CODE

The following is the generic format of how data was organized for use in the Vehicle Routing Problem model implemented in GAMS (see Appendix C).

```
SCALARS
        gS   "size of group of vehicles to look at" /2/;
SET
        t  time period /T1*T42/ {14 hours based upon time step of 20 min}
                {T1 denotes time 0}
        c  commodity /mre, water, fuel, ammo/
        v  vehicle number /V1*V22/  {T/E Transportation Support: 22 vehicles}
        m  vehicle type /LVS, FTon, HMMWV/
        i  nodes in the network
          / *** List all of the nodes in the network here. *** /
        vehtype(v,m) associate every vehicle with a type of truck
          /(V1*V3).HMMWV, (V4*V8).FTon, (V9*V22).LVS/
        orig(v,i) establish the location of the CSSE origin for each set of vehicles
          /(V1*V22).W0/
        arc(i,i) arcs in the network;
        ALIAS (v,vv);
        ALIAS (i,j);
        ALIAS (t,tt);

*----PARAMETERS
TABLE dem(i,c) demand of c at node i {STONS}
        mre  water  fuel  ammo
```

```
*** List all of the nodes and their appropriate demands as a table here.***
PARAMETER
        totDem(i)  sum of demand at node i {STONS};
          {Used for D(v,i,t).  If totDem(i) = 0, do not start delivery.}
         {Also used in establishing priorities for delivering.}
        totDem(i) = sum(c,dem(i,c));
TABLE q(m,c) capacity of c in vehicle type m {STONS}
                        mre   water  fuel  ammo
        LVS             20    18.78  15.75   20
        FTon            5      3.76    3.15     5
        HMMWV  1.187     0.0      0.0      1.187 ;
PARAMETER
         trav(i,j) travel time between node i & j {time steps of 20 min periods}
  / *** List the travel times for each of the arcs here based upon a constant speed
        on the vehicle.  Note what the distance measurement is for the
        simulation, i.e. miles, kilometers, …***   /;
PARAMETER
        travv(i,j) time step for travel;
        travv(i,j) = trav(i,j) - 1;
PARAMETER
        minA(v,i) variable savings method for the model, min arrival time
   / *** List the minimum time it takes to travel to distant nodes in order to save
        variables in the GAMS calculation.  This may be overcome by writing a
        more robust heuristic. (i.e.: (V1*V22).GR5   3) ***  /;
        minA(v,i)$(orig(v,i)) = 1;
PARAMETERS
         maxT(v) maximum route time allowed for vehicle v {time steps};
        maxT(v)=30 {10 hour operating period with time step of 20 min};
PARAMETER
        fuel(v,m) max time vehicle v may travel due to fuel limitations;
```

```
        fuel(v,"LVS") = 27;  {time step of 20 min intervals}
        fuel(v,"FTON") = 20;
        fuel(v,"HMMWV") = 44;
PARAMETERS
        early(i) earliest time for node i {time period, start of window}
          {based upon demand point}
          /BT1=10, LL4=20, D1=11, NP5=21
          QL3=30, EL1=25, GP1=21 /
        late(i) latest arrival time for node i {time period, end of time window}
          /BT1=16, LL4=25, D1=17, NP5=25
          QL3=32, EL1=28, GP1=27/;
PARAMETER
        beta(i,c) penalty for an unmet demand {regret/STON};
        beta(i,c) = 1;
PARAMETER
        b(i,m) delivery time at node i for type of vehicle m {time steps};
        b(i,"LVS") = 4;
        b(i,"FTon") = 2;
        b(i,"HMMWV") = 1;
PARAMETER
        bb(i,m) time step for delivery;
        bb(i,m) = b(i,m) - 1;
PARAMETER
        maxq(m) max capacity for vehicle v of type m {STONS}
          /LVS=20, FTon=5, HMMWV=1.187/;
        {Define arcs in the network based on whether a travel time exists.}
        arc(i,j)$(trav(i,j) GT 0) = YES;
SCALARS
        epsilon  "small value used to minimize distance"  /.00001/
        n    "small value used in BigM calculations"  /.01/
```

```
bmw  "big M calculation for water"
bmf  "big M calculation for fuel";
  {BigM calculations for fuel and water}
bmw = q("LVS","water")+q("LVS","ammo")+n;
bmf = q("LVS","fuel")+n;
display n, bmw, bmf;
```

THIS PAGE INTENTIONALLY LEFT BLANK

## APPENDIX C. KEY GENERAL ALGEBRAIC MODELING SYSTEM (GAMS) PROGRAM CODE / VEHICAL ROUTING PROBLEM HEURISTIC CHARTS

A complete copy of the VRP model implementation in GAMS code used in this thesis may be obtained from Professor Javier Salmeron of the Operations Research Department of Naval Postgraduate School. This section highlights some of the key areas of the optimization code utilized in the thesis. It does not include the entire program for space saving reasons. Sets and data used in the code are described in Appendix B.

### *** OBJECTIVE FUNCTION ***

```
OBJ..   TOTUNMET
        =E=
        sum((i,c), beta(i,c)*U(i,c))
        + sum((v,i,j,t)$(ord(t) GT late(i) and arc(i,j)
            and ord(v) GE vmin and ord(v) LE vmax),
              epsilon*X(v,i,j,t))
        + sum((v,i,t)$(ord(t) GE early(i) and ord(t) LE late(i)
            and ord(v) GE vmin and ord(v) LE vmax ),
              epsilon*D(v,i,t));
```

### *** EQUATIONS AND INEQUALITIES ***

Each equation is discussed thoroughly in Chapter IV.

```
SERVICE(v,c)$(ord(v) GE vmin and ord(v) LE vmax)..
        sum((i,t)$(ord(t) GE early(i) and ord(t) LE late(i)
                   and dem(i,c) GT 0),
        S(v,i,c,t))
        =E=
        L(v,c);

DELIVPT(v,i,c,t)$(ord(v) GE vmin and ord(v) LE vmax
       and ord(t) GE early(i) and ord(t) LE late(i) and dem(i,c) GT 0)..
       S(v,i,c,t)
       =L=
       dem(i,c)*D(v,i,t);



ELASTIC(i,c)$(dem(i,c) GT 0)..
      sum((t,v)$(ord(t) GE early(i) and ord(t) LE late(i)
      and ord(v) GE vmin and ord(v) LE vmax),
      S(v,i,c,t))
      +U(i,c)
      =E=
      dem(i,c);
```

```
LOADCAP(v)$(ord(v) GE vmin and ord(v) LE vmax)..
      sum(c,L(v,c))
      =L=
      sum(m$(vehtype(v,m)),maxq(m));

BALANCE(v,i,t)$(ord(t) LT card(t) and ord(v) GE vmin
      and ord(v) LE vmax)..
      W(v,i,t)+sum(m$(vehtype(v,m) and totDem(i) GT 0),D(v,i,t-
      bb(i,m)))+
      sum(j$(arc(j,i)),X(v,j,i,t-travv(j,i)))
      =E=
      W(v,i,t+1)+D(v,i,t+1)$(totDem(i) GT 0)+
      sum(j$(arc(i,j)),X(v,i,j,t+1));

SENDV(v)$((vehtype(v,"LVS") or vehtype(v,"FTon"))
      and ord(v) GE vmin and ord(v) LE vmax)..
      LW(v) + LF(v)
      =L=
      1;

SENDW(V)$((vehtype(v,"LVS") or vehtype(v,"FTon"))
      and ord(v) GE vmin
      and ord(v) LE vmax)..
      L(v,"water") + L(v,"ammo")
      =L=
      bmw*LW(v);

SENDF(V)$((vehtype(v,"LVS") or vehtype(v,"FTon"))
      and ord(v) GE vmin and ord(v) LE vmax)..
      L(v,"fuel")
      =L=
      bmf*LF(v);

SHIFT_TIME(v,t)$(ord(t) GE maxT(v) and ord(v) GE vmin
      and ord(v) LE vmax)..
      sum((i,j)$(orig(v,i) and arc(i,j)), X(v,i,j,t-maxT(v)))
      =L=
      sum(i$(orig(v,i)), W(v,i,t));

SHIFT_FUEL(v)$(ord(v) GE vmin and ord(v) LE vmax)..
      sum((i,j,t)$(arc(i,j)), trav(i,j)*X(v,i,j,t))
      =L=
      sum(m$(vehtype(v,m)), fuel(v,m));

BACK(v,i,j,t)$(arc(i,j) and arc(j,i) and ord(v) GE vmin
      and ord(v) LE vmax)..
      X(v,i,j,t) + X(v,j,i,t+travv(i,j))
      =L= 1;
```

## *** BOUND AND FIX VARIABLES ***

```
{Upper bounds for loading of each quantity}
{Cannot load more than the max capacity of a vehicle type.}
L.up(v,c)$(ord(v) GE vmin and ord(v) LE vmax) =
      sum(m$(vehtype(v,m)),q(m,c));
```

```
{initial/final conditions}
X.fx(v,i,j,t)$(arc(i,j) and not orig(v,i) and ord(t) EQ 2
      and ord(v) GE vmin and ord(v) LE vmax) = 0.0;

X.fx(v,i,j,t)$(arc(i,j) and (ord(t) EQ 1 or ord(t) LT minA(v,i))
      and ord(v) GE vmin and ord(v) LE vmax) = 0.0;

W.fx(v,i,t)$(not orig(v,i) and (ord(t) EQ 1 or ord(t) LT minA(v,i))
      and ord(v) GE vmin and ord(v) LE vmax) = 0.0;

W.fx(v,i,t)$(orig(v,i) and ord(t) EQ 1
      and ord(v) GE vmin and ord(v) LE vmax) = 1.0;

W.fx(v,i,t)$(orig(v,i) and ord(t) EQ card(t)
      and ord(v) GE vmin and ord(v) LE vmax) = 1.0;

D.fx(v,i,t)$((ord(t) EQ 1 or ord(t) LT early(i)
      or ord(t) LT minA(v,i)) and totDem(i) GT 0
      and ord(v) GE vmin and ord(v) LE vmax) = 0.0;

{Fix any variable with subindex v, if ord(v)<vmin, to its current }
{value.  We have already decided the values in the previous       }
{iterations of the loop.                                          }
X.fx(v,i,j,t)$(ord(v) < vmin) = X.L(v,i,j,t);
W.fx(v,i,t)$(ord(v) < vmin) = W.L(v,i,t);
D.fx(v,i,t)$(ord(v) < vmin) = D.L(v,i,t);

W.fx(v,i,t)$(orig(v,i) and ord(t) EQ card(t)
      and ord(v) > vmax) = 1.0;
```

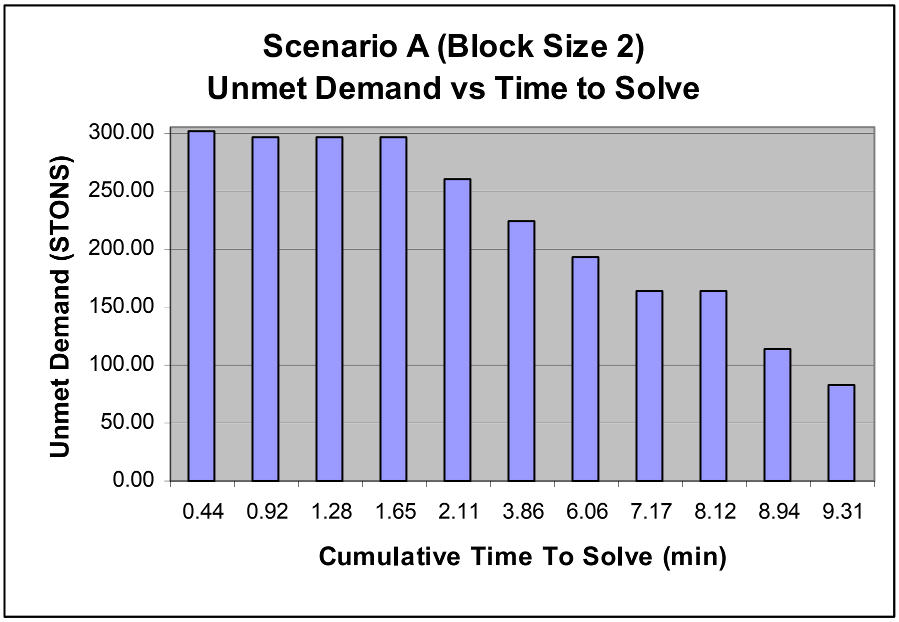


***Figure 19. Scenario A (Block Size 2) Unmet Demand vs Time To Solve***
*This figure depicts demand being decremented as the heuristic steps through a block size of two vehicles at a time. It also demonstrates how quickly this scenario could be solved with a heuristic.*

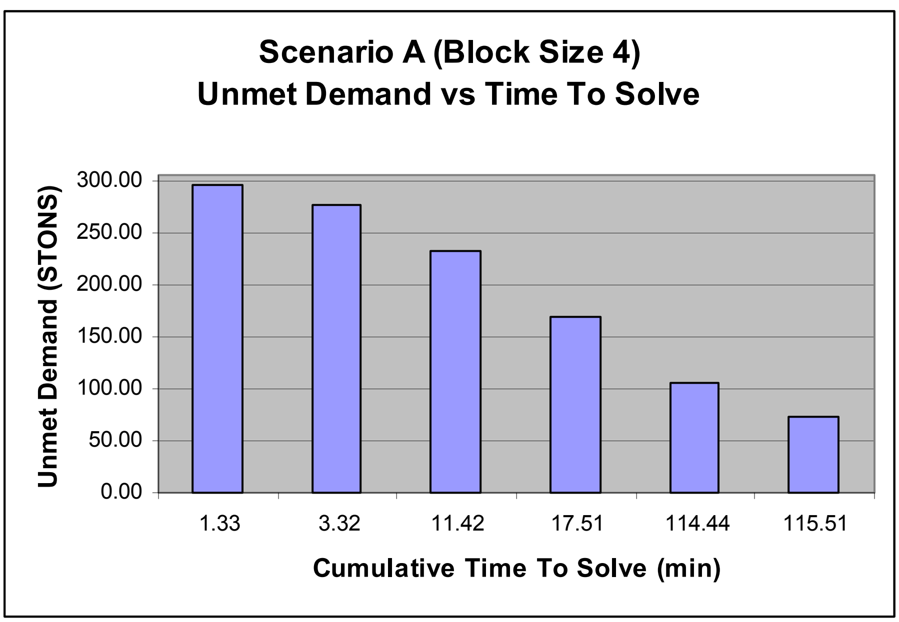


***Figure 20. Scenario A (Block Size 4) Unmet Demand vs Time To Solve***
*This figure depicts demand being decremented as the heuristic steps through a block size of four vehicles at a time. There is less unmet demand, but there is also a tradeoff with time to solve.*

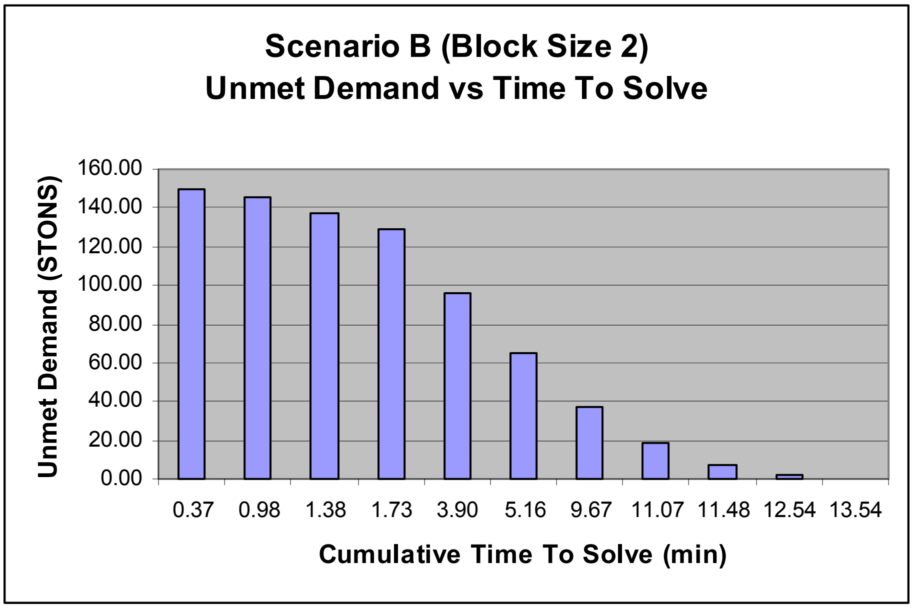


***Figure 21. Scenario B (Block Size 2) Unmet Demand vs Time To Solve***

*This figure depicts demand being decremented as the heuristic steps through a block size of two vehicles at a time. It also demonstrates how quickly this scenario could be solved with a heuristic.*

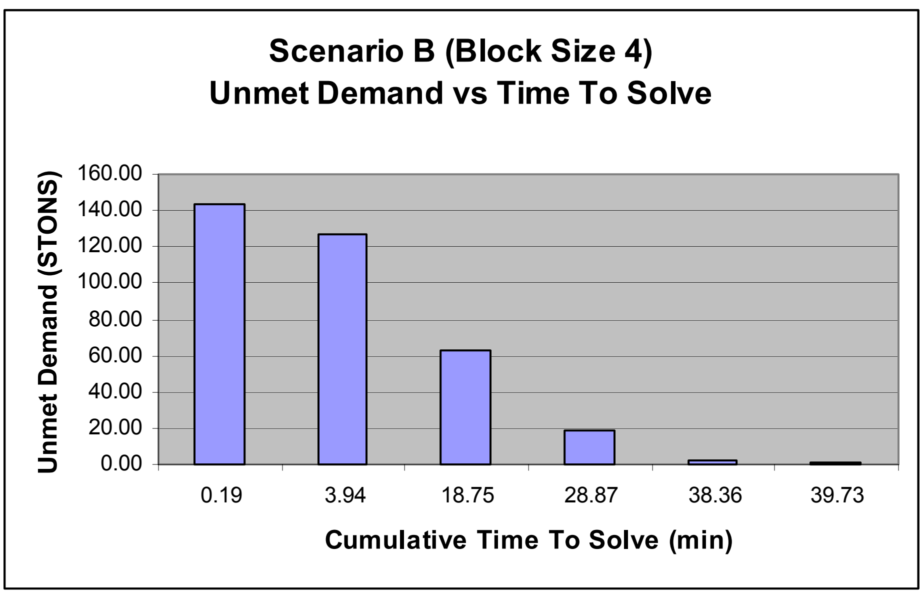


***Figure 22. Scenario B (Block Size 4) Unmet Demand vs Time To Solve***

*The quantity of unmet demand at the end is not much better than when using the heuristic with two vehicles at a time. This block size also takes longer than the previous block size.*

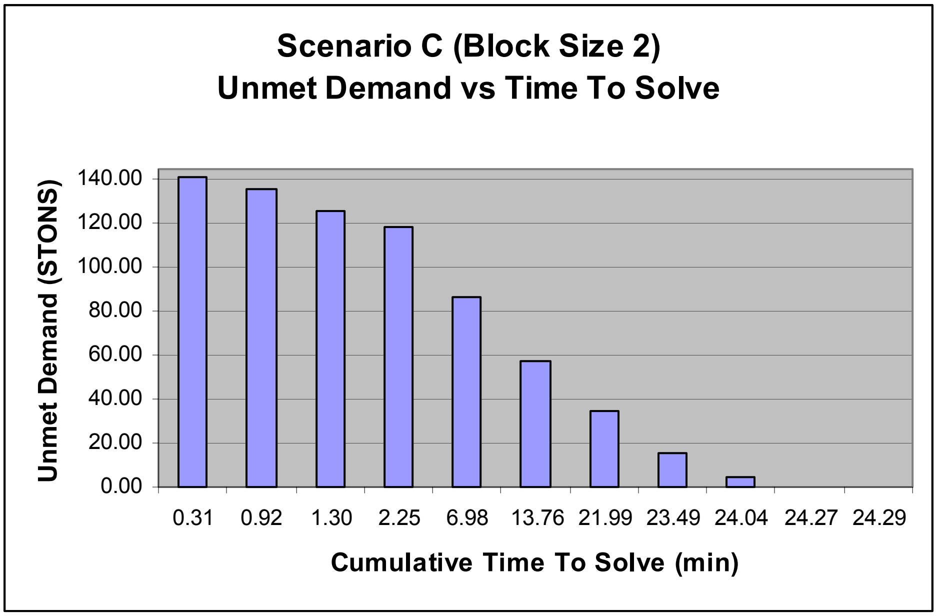


***Figure 23. Scenario C (Block Size 2) Unmet Demand vs Time To Solve***

*This figure depicts demand being decremented as the heuristic steps through a block size of two vehicles at a time. It also demonstrates how quickly this scenario could be solved with a heuristic.*

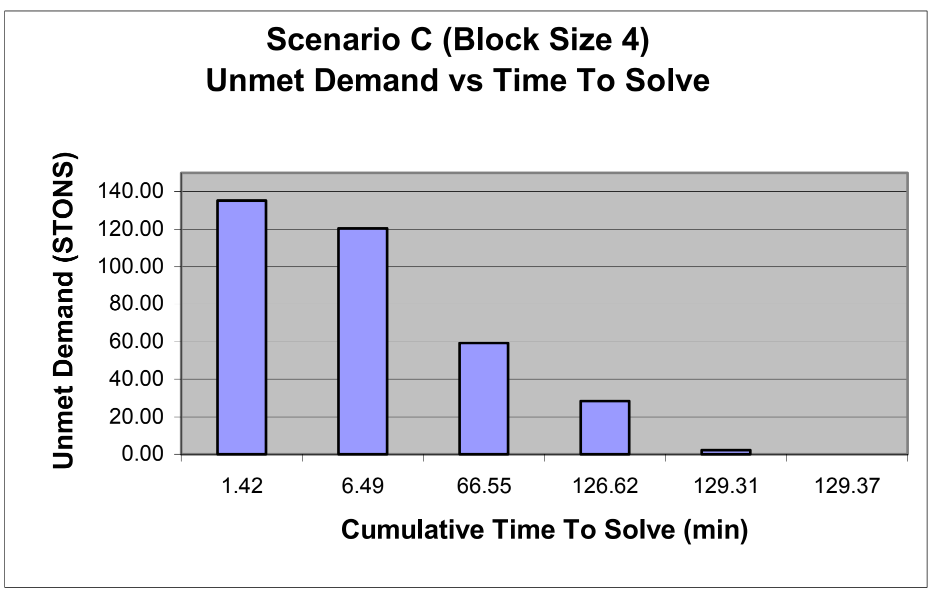


***Figure 24. Scenario C (Block Size 4) Unmet Demand vs Time To Solve***

*This figure depicts demand being decremented as the heuristic steps through a block size of four vehicles at a time. Block size 2 and 4 both end up with unmet demand of zero but this block size takes longer.*

# APPENDIX D. KEY SOURCE CODE FOR SIMULATION PROGRAM

A complete copy of all the simulation code used in this thesis may be obtained from Professors Arnold Buss, or Gordon Bradley of the Operations Research Department of the Naval Postgraduate School. This section highlights a few of the key areas of the simulation code utilized in the thesis. It does not include the entire program for space saving reasons.

**Properties Files**

Two property file types were used. All other data input into the simulation model came from the VRP optimization model output and an XML file with the road network information. The following describes the generic format of the main properties file and a properties file used for a vehicle type.

The key parameters of the main properties file are as listed:

- output file with a file location of where to send information on a simulation run;
- number of replications desired along with a truncation point;
- number of different vehicle types and specific vehicle types used;
- properties file location for each type of vehicle;
- side numbers of vehicles so a vehicle may be identified;
- travel speed of the vehicle (miles, kilometers, or seconds per hour);
- probability of checkpoint occurrence and its distribution properties;
- wait time properties;
- delivery time windows;
- and the time step used in the VRP program.

The key parameters of the vehicles properties files are as listed:

- categories of payload that may be loaded;
- loading characteristics such as maximum load as well as its distribution parameters;
- the probability of a delay in loading to occur and the delay distribution properties;

- and the unloading distribution and its properties.

**Properties file sorter**

This was important because it allowed the program to point towards a specialized properties file based upon the particular vehicle type used at the time. This allowed for much more manageable properties files sizes.

```
// constructor method
  public PropsFileSorter(Properties theProps) {
    numVehTypes = Integer.parseInt(theProps.get("numVehTypes").toString());
    vehNames = new String[numVehTypes];
    fileNames = new String[numVehTypes];
    for(int i=0; i<numVehTypes; i++){
      vehNames[i] = theProps.get(Integer.toString(i)).toString();
    }
    setProperty(theProps);
  }
// instance methods
 public Properties getPropsFile(String vehType){
   Properties thePropFile = new Properties();
   for(int i=0; i<numVehTypes; i++){
     if(vehNames[i].equals(vehType)){
       String file = props.get(vehType).toString();
       try{
         thePropFile.load(new FileInputStream(file));
       }catch(FileNotFoundException e){ System.err.println(e);}
       catch(IOException e){System.err.println(e);}
     }
   }
   return thePropFile;
 }
 public String getPropsFileName(String vehType){
   String propFileName = null;
   for(int i=0; i<numVehTypes; i++){
     if(vehNames[i].equals(vehType)){
       propFileName = props.get(vehType).toString();
     }
   }
   return propFileName;
 }
 public void setProperty(Properties theProps){props = theProps;}
```

**Conversions**

The simulation also required that a time conversion program be written since the VRP optimization program used time steps of 20 minutes. There was also a requirement to convert the speed to seconds per hour since all distances were in geogrphical seconds.

**Triangular Distribution used for Loading**

The triangular distribution used for the loading of the vehicles is also worth mentioning since it is a method used by many simulation practitioners (Law & Kelton 2000).

```
public double generate(){
  double u;
  double v;
  double y;

  do{
        u = rng.draw();
        v = rng.draw();
        y = left + (right - left) * v;
  }
  while ( ((y<center) && (u > ((y-left)/(center-left)))) ||
        ((y>center) && (u > ((right-y)/(right-center)))) );
  return y;
```

**Network program**

This class allowed the program to retreive information desired about the road network from the XML file by extending a DOM Parser program. The key instance methods are as listed. The parameters in the parenthesis indicate what needs to be passed to the method and the type after the 'public' indicates what will be returned

Get the arc length, whether specific coordinates are passed or specific node names are passed.

- public double getArcLength(Coordinate from, Coordinate to)
- public double getArcLength(String from, String to)

Get the node name, based on its coordinates.

- public String getNodeAt(Coordinate c){

Given a node name, return its coordinates.

- public Coordinate getNodeCoord(String nodeName)

THIS PAGE LEFT INTENTIONALLY BLANK

# APPENDIX E. OUTPUT OF THE PROGRAMS

## A. VEHICLE ROUTING PROBLEM WITH TIME WINDOWS OUTPUT

The VRP output gives a route plan for each vehicle in order to meet all the demands within the correct time windows. It indicates which vehicles should be used, what should be loaded on each vehicle, and where each commodity should be delivered. It also outputs the total unmet demand and the total computer resource usage in seconds to solve each problem given. This first set of output is a sampling of the output from the optimization portion of this thesis.

Total resource usage in seconds: 2259.73

TOTAL UNMET DEMAND WITH PENALTIES;

0.00

…

…

…

Vehicle V11

| Time Step | Vehicle Status | Location |
|---|---|---|
| T1 | Wait at node | W0 |
| T2 | Enroute from | W0 to W8 |
| T3 | Enroute from | W8 to P1 |
| T5 | Enroute from | P1 to P3 |
| T7 | Enroute from | P3 to D1 |
| T10 | Enroute from | D1 to BT1 |
| T14 | Deliver at node | BT1 |
| T18 | Enroute from | BT1 to L1 |
| T21 | Enroute from | L1 to CP2 |
| T23 | Wait at node | CP2 |
| T24 | Enroute from | CP2 to P1 |

| | | | | |
|---|---|---|---|---|
| T29 | Enroute from | P1 | to | W8 |
| T31 | Enroute from | W8 | to | W0 |
| T32 | Wait at node | W0 | | |
| T33 | Wait at node | W0 | | |

…

…

…

L, quantity of commodity loaded in vehicle v:

| | mre | water | fuel | ammo |
|---|---|---|---|---|
| V1 | 0.00 | 0.00 | 0.00 | 0.00 |
| … | | | | |
| … | | | | |
| … | | | | |
| V21 | 0.00 | 0.00 | 3.50 | 0.00 |
| V22 | 0.00 | 0.00 | 15.75 | 0.0 |

S, quantity of commodity served by vehicle v at node i in time period t:

| | TimeStep | Node | mre | water | fuel | ammo |
|---|---|---|---|---|---|---|
| V1 | | | | | | |
| … | | | | | | |
| … | | | | | | |
| … | | | | | | |
| V20 | T15 | D1 | 0.30 | 1.70 | 0.00 | 0.70 |
| | T25 | NP5 | 1.20 | 6.90 | 0.00 | 3.20 |
| V21 | T25 | NP5 | 0.00 | 0.00 | 3.50 | 0.00 |
| V22 | T25 | NP5 | 0.00 | 0.00 | 15.75 | 0.00 |

U, quantity of unmet demand:

| mre | water | fuel | ammo |
|---|---|---|---|

0.00 0.00 0.00 0.00

ALL DEMANDS HAVE BEEN MET

## B. SIMULATION OF THE LOCCC CONCEPT OUTPUT

The second set of output comes from the simulation . The output from above is an input parameter into the simulation model. The output of the simulation model is formatted so that a quick examination of the MOE's may be made. A more detailed understanding is obtained through the exploratory analysis. This is an example of the output format:

95% Confidence Intervals

Ability to meet every Time Window is: 0.41645 +/- 0.02489 %

Mean Arrival Time to the Time Window: -0.04889 +/- 0.08821 hrs.

Percent of the time vehicles are early: 0.26636 +/- 0.02963 %

Mean number of vehicles that arrive early: 3.48000 +/- 0.47430

Mean amount of time vehicles are early: 2.81616 +/- 0.28585 hrs.

Mean number of vehicles that arrive late: 11.82000 +/- 1.00223

Mean amount of time vehicles are late: 1.09872 +/- 0.09097 hrs.

Mean delay time along the route: 1.44863 +/- 0.12953 hrs.

Total deliveries made: 27

Total tonnage hauled by all vehicles: 152.08000 STONS

Total requisition quantity by all vehicles: 152.52000 STONS

Percent of total demand satisfied: 0.99712 %.

Number of roads (arcs) used: 259.00000

Total distance traveled: 1098.55811 miles.

Total ton-miles:167068.71746

Arrive times of every single vehicle:

…

…

…

## C. EXPLORATORY ANALYSIS OUTPUT

**$2^{4-1}$ Resolution IV Designs:**

| | | FACTOR | | | | | | FACTOR | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Standard Order | Run Order | Speed | Load | Delay Load | Wait | Standard Order | Run Order | Speed | Load | Delay Load | Wait |
| Scenario C, Exact Method | | | | | | Scenario C, Heuristic Block 2 | | | | | |
| 1 | 1 | -1 | -1 | -1 | -1 | 3 | 33 | -1 | +1 | -1 | +1 |
| 3 | 2 | -1 | +1 | -1 | +1 | 6 | 34 | +1 | -1 | +1 | -1 |
| 6 | 3 | +1 | -1 | +1 | -1 | 2 | 35 | +1 | -1 | -1 | +1 |
| 5 | 4 | -1 | -1 | +1 | +1 | 5 | 36 | -1 | -1 | +1 | +1 |
| 4 | 5 | +1 | +1 | -1 | -1 | 4 | 37 | +1 | +1 | -1 | -1 |
| 8 | 6 | +1 | +1 | +1 | +1 | 1 | 38 | -1 | -1 | -1 | -1 |
| 7 | 7 | -1 | +1 | +1 | -1 | 7 | 39 | -1 | +1 | +1 | -1 |
| 2 | 8 | +1 | -1 | -1 | +1 | 8 | 40 | +1 | +1 | +1 | +1 |
| Scenario B, Exact Method | | | | | | Scenario A, Heuristic Block 4 | | | | | |
| 7 | 9 | -1 | +1 | +1 | -1 | 1 | 41 | -1 | -1 | -1 | -1 |
| 3 | 10 | -1 | +1 | -1 | +1 | 2 | 42 | +1 | -1 | -1 | +1 |
| 2 | 11 | +1 | -1 | -1 | +1 | 3 | 43 | -1 | +1 | -1 | +1 |
| 1 | 12 | -1 | -1 | -1 | -1 | 7 | 44 | -1 | +1 | +1 | -1 |
| 8 | 13 | +1 | +1 | +1 | +1 | 5 | 45 | -1 | -1 | +1 | +1 |
| 4 | 14 | +1 | +1 | -1 | -1 | 4 | 46 | +1 | +1 | -1 | -1 |
| 6 | 15 | +1 | -1 | +1 | -1 | 8 | 47 | +1 | +1 | +1 | +1 |
| 5 | 16 | -1 | -1 | +1 | +1 | 6 | 48 | +1 | -1 | +1 | -1 |
| Scenario B, Heuristic Block 2 | | | | | | Scenario B, Heuristic Block 4 | | | | | |
| 1 | 17 | -1 | -1 | -1 | -1 | 6 | 49 | +1 | -1 | +1 | -1 |
| 5 | 18 | -1 | -1 | +1 | +1 | 2 | 50 | +1 | -1 | -1 | +1 |
| 3 | 19 | -1 | +1 | -1 | +1 | 5 | 51 | -1 | -1 | +1 | +1 |
| 8 | 20 | +1 | +1 | +1 | +1 | 7 | 52 | -1 | +1 | +1 | -1 |
| 2 | 21 | +1 | -1 | -1 | +1 | 8 | 53 | +1 | +1 | +1 | +1 |
| 7 | 22 | -1 | +1 | +1 | -1 | 3 | 54 | -1 | +1 | -1 | +1 |
| 4 | 23 | +1 | +1 | -1 | -1 | 1 | 55 | -1 | -1 | -1 | -1 |
| 6 | 24 | +1 | -1 | +1 | -1 | 4 | 56 | +1 | +1 | -1 | -1 |
| Scenario A, Heuristic Block 2 | | | | | | Scenario A, Exact Method | | | | | |
| 2 | 25 | +1 | -1 | -1 | +1 | 4 | 57 | +1 | +1 | -1 | -1 |
| 5 | 26 | -1 | -1 | +1 | +1 | 2 | 58 | +1 | -1 | -1 | +1 |
| 4 | 27 | +1 | +1 | -1 | -1 | 3 | 59 | -1 | +1 | -1 | +1 |
| 3 | 28 | -1 | +1 | -1 | +1 | 6 | 60 | +1 | -1 | +1 | -1 |
| 1 | 29 | -1 | -1 | -1 | -1 | 5 | 61 | -1 | -1 | +1 | +1 |
| 6 | 30 | +1 | -1 | +1 | -1 | 7 | 62 | -1 | +1 | +1 | -1 |
| 7 | 31 | -1 | +1 | +1 | -1 | 8 | 63 | +1 | +1 | +1 | +1 |
| 8 | 32 | +1 | +1 | +1 | +1 | 1 | 64 | -1 | -1 | -1 | -1 |
| Factor Label | | A | B | C | D | Factor Level | | A | B | C | D |

| Standard Order | Run Order | Speed | Load | Delay Load | Wait |
|---|---|---|---|---|---|
| Scenario C, Heuristic Block 4 | | | | | |
| 7 | 65 | -1 | +1 | +1 | -1 |
| 8 | 66 | +1 | +1 | +1 | +1 |
| 5 | 67 | -1 | -1 | +1 | +1 |
| 6 | 68 | +1 | -1 | +1 | -1 |
| 1 | 69 | -1 | -1 | -1 | -1 |
| 2 | 70 | +1 | -1 | -1 | +1 |
| 3 | 71 | -1 | +1 | -1 | +1 |
| 4 | 72 | +1 | +1 | -1 | -1 |
| Factor Label | | A | B | C | D |

**S-Plus Code for batch means and the autocorrelation function:**

The technique of batch means was performed for all data collected. A statistical package by the name of R was used (Ihaka & Gentleman 1996). The code for obtaining all of the batch means is as follows:

```
function(data)
{       corr <- acf(data, 5000)
        first <- corr$lag[corr$acf < 0.1][1]
        truncationPoint <- 4 * first
        cutOne <- length(data) - truncationPoint
        cutTwo <- cutOne - cutOne %% 8
        if(length(data)/2 < truncationPoint +  cutOne %% 8) {
                return("Not enough data to continue")
        }
        data <- data[(truncationPoint + 1 + cutOne %% 8):length(data)]
        index <- 1
        batchSizeUsed <- length(data)/8
        numberBatchesUsed <- 8
        X <- matrix(data, nrow = 8)
        XrowMeans <- round(apply(X, 1, mean), 2)
        b <- length(XrowMeans)
        XrowVar <- round(apply(X, 1, var), 2)
        XrowCov <- round(gammaEst(X), 2)
        grandMean <- sum(XrowMeans)/b
        grandVar <- var(XrowMeans)
        CI <- c(grandMean - qt(0.975, b - 1) * sqrt(grandVar/b), grandMean +
                qt(0.975, b - 1) * sqrt( grandVar/b))
        results <- list("Truncation Point" = truncationPoint + cutOne %% 8,
                "Number Data Remaining" = length(data), "Batch Size Used"
                 = batchSizeUsed,
```

```
                "Number Batches Used" = numberBatchesUsed,
                "Mean of Each Batch" =  XrowMeans,
                "Variance in Each Batch" =  XrowVar,
                "Batch Covariance(nearest hundredth)" = XrowCov,
                "Grand Mean" = grandMean,
                "Variation of Batch Means" =  grandVar, "95% CI" = CI)
        return(results)
    }
```

**Summary Tables of Results of the Simulation:**

Note: All intervals are 95 % Confidence Intervals. Also in the Arrival Time MOEs tables, negative numbers in the context of the batch means arrival time indicate late arrival times and positive numbers indicate early arrival times.

**Delivery MOEs**

| Number of deliveries | Tons Hauled (STONS) | % Demand Satisfied | Demand Quantity (STONS) | Distance Traveled (miles) | Ton-Miles |
|---|---|---|---|---|---|
| Scenario A, Heuristic Block 2 | | | | | |
| 21 | 222.98 | 73.2 % | 304.64 | 985.25 | 219691.05 |
| Scenario A, Heuristic Block 4 | | | | | |
| 23 | 231.32 | 75.9 % | 304.64 | 1046.07 | 241977.40 |
| Scenario A, Exact Method | | | | | |
| 25 | 243.19 | 79.8% | 304.64 | 1119.94 | 272359.20 |
| Scenario B, Heuristic Block 2 | | | | | |
| 27 | 152.08 | 99.7 % | 152.52 | 1098.56 | 167068.72 |
| Scenario B, Heuristic Block 4 | | | | | |
| 27 | 151.54 | 99.4 % | 152.52 | 1114.46 | 168885.63 |
| Scenario B, Exact Method | | | | | |
| 26 | 149.64 | 98.1 % | 152.52 | 1162.91 | 174018.58 |
| Scenario C, Heuristic Block 2 | | | | | |
| 23 | 143.85 | 100 % | 143.85 | 1048.08 | 150766.24 |
| Scenario C, Heuristic Block 4 | | | | | |
| 24 | 143.85 | 100 % | 143.85 | 1102.75 | 158631.06 |
| Scenario C, Exact Method | | | | | |
| 18 | 143.85 | 100 % | 143.85 | 800.81 | 115197.12 |

| Run | Ability to Meet Windows (%) | Batch Mean Arrival Time | % of time early | Mean Number Early | Mean Time Early (hrs) | Mean Number Late | Mean Time Late (hrs) | Mean Delay (hrs) |
|---|---|---|---|---|---|---|---|---|
| Scenario A, Heuristic Block 2 | | | | | | | | |
| 25 | 0.416 +/- 0.025 | -0.04 +/- 0.088 | 0.266 +/- 0.030 | 3.48 +/- 0.474 | 2.82 +/- 0.286 | 10.22 +/- 0.902 | 1.099 +/- 0.091 | 1.449 +/- 0.130 |
| 26 | 0.582 +/- 0.022 | 0.53 +/- 0.071 | 0.359 +/- 0.022 | 11.66 +/- 0.695 | 1.836 +/- 0.154 | 1.34 +/- 0.388 | 1.42 +/- 0.354 | 1.45 +/- 0.130 |
| 27 | 0.337 +/- 0.024 | 0.023 +/- 0.074 | 0.285 +/- 0.033 | 2.86 +/- 0.110 | 2.92 +/- 0.298 | 14.4 +/- 0.363 | 0.688 +/- 0.037 | 1.475 +/- 0.114 |
| 28 | 0.619 +/- 0.022 | 0.454 +/- 0.072 | 0.331 +/- 0.022 | 10.04 +/- 0.816 | 1.80 +/- 0.169 | 1.68 +/- 0.450 | 1.405 +/- 0.331 | 1.45 +/- 0.130 |
| 29 | 0.608 +/- 0.021 | 0.516 +/- 0.058 | 0.374 +/- 0.021 | 13.22 +/- 0.232 | 1.43 +/- 0.138 | 0.100 +/- 0.086 | 0.204 +/- 0.038 | 1.47 +/- 0.114 |
| 30 | 0.513 +/- 0.025 | 0.167 +/- 0.075 | 0.216 +/- 0.026 | 3.00 +/- 0.0 | 3.054 +/- 0.299 | 9.56 +/- 0.288 | 0.696 +/- 0.041 | 1.47 +/- 0.114 |
| 31 | 0.607 +/- 0.021 | 0.507 +/- 0.059 | 0.370 +/- 0.022 | 12.9 +/- 0.265 | 1.43 +/- 0.141 | 0.26 +/- 0.138 | 0.186 +/- 0.034 | 1.47 +/- 0.114 |
| 32 | 0.405 +/- 0.025 | -0.075 +/- 0.089 | 0.265 +/- 0.030 | 3.30 +/- 0.478 | 2.89 +/- 0.291 | 12.2 +/- 0.969 | 1.106 +/- 0.089 | 1.45 +/- 0.130 |
| Scenario A, Heuristic Block 4 | | | | | | | | |
| 41 | 0.597 +/- 0.023 | 0.56 +/- 0.045 | 0.390 +/- 0.023 | 12.56 +/- 0.183 | 1.47 +/- 0.135 | 0.0 +/- 0.0 | 0.189 +/- 0.052 | 1.100 +/- 0.068 |
| 42 | 0.405 +/- 0.026 | -0.046 +/- 0.103 | 0.299 +/- 0.032 | 3.62 +/- 0.477 | 2.71 +/- 0.260 | 10.24 +/- 0.623 | 1.21 +/- 0.108 | 1.09 +/- 0.078 |
| 43 | 0.605 +/- 0.023 | 0.474 +/- 0.110 | 0.363 +/- 0.023 | 10.52 +/- 0.767 | 1.75 +/- 0.157 | 0.98 +/- 0.404 | 2.48 +/- 0.535 | 1.09 +/- 0.078 |
| 44 | 0.600 +/- 0.022 | 0.545 +/- 0.065 | 0.385 +/- 0.023 | 12.22 +/- 0.232 | 1.47 +/- 0.138 | 0.0 +/- 0.0 | 0.190 +/- 0.043 | 1.10 +/- 0.068 |
| 45 | 0.546 +/- 0.024 | -0.153 +/- 0.103 | 0.354 +/- 0.022 | 2.0 +/- 0.512 | 0.978 +/- 0.154 | 9.54 +/- 0.287 | 1.1 +/- 0.110 | 1.10 +/- 0.078 |
| 46 | 0.420 +/- 0.027 | -0.009 +/- 0.058 | 0.227 +/- 0.031 | 2.10 +/- 0.086 | 3.156 +/- 0.325 | 10.48 +/- 0.316 | 0.872 +/- 0.036 | 1.10 +/- 0.068 |
| 47 | 0.395 +/- 0.026 | -0.071 +/- 0.169 | 0.304 +/- 0.033 | 3.62 +/- 0.470 | 2.68 +/- 0.264 | 10.52 +/- 0.663 | 1.23 +/- 0.106 | 1.09 +/- 0.078 |
| 48 | 0.472 +/- 0.027 | 0.133 +/- 0.076 | 0.258 +/- 0.029 | 3.32 +/- 0.194 | 2.47 +/- 0.304 | 8.56 +/- 0.200 | 0.758 +/- 0.024 | 1.10 +/- 0.068 |
| Scenario A, Exact Method | | | | | | | | |
| 57 | 0.475 +/- 0.040 | -0.076 +/- 0.059 | 0.277 +/- 0.044 | 4.40 +/- 0.319 | 0.644 +/- 0.930 | 9.050 +/- 0.386 | 0.572 +/- 0.055 | 0.691 +/- 0.037 |
| 58 | 0.420 +/- 0.038 | 0.025 +/- 0.165 | 0.315 +/- 0.046 | 5.00 +/- 0.568 | 2.59 +/- 0.319 | 11.15 +/- 1.22 | 1.24 +/- 0.180 | 1.31 +/- 0.104 |
| 59 | 0.359 +/- 0.024 | -0.094 +/- 0.056 | 0.333 +/- 0.032 | 4.48 +/- 0.355 | 2.56 +/- 0.207 | 13.14 +/- 0.738 | 1.21 +/- 0.100 | 1.27 +/- 0.064 |
| 60 | 0.532 +/- 0.038 | 0.065 +/- 0.041 | 0.305 +/- 0.040 | 6.35 +/- 0.314 | 0.694 +/- 0.085 | 6.40 +/- 0.535 | 0.415 +/- 0.057 | 0.691 +/- 0.037 |
| 61 | 0.614 +/- 0.030 | 0.565 +/- 0.136 | 0.364 +/- 0.030 | 12.44 +/- 0.62 | 2.00 +/- 0.197 | 0.32 +/- 0.230 | 3.89 +/- 0.583 | 1.29 +/- 0.092 |
| 62 | 0.605 +/- 0.033 | 0.478 +/- 0.156 | 0.378 +/- 0.033 | 13.5 +/- 0.356 | 1.66 +/- 0.197 | 0.0 +/- 0.0 | 4.58 +/- 0.50 | 1.31 +/- 0.085 |
| 63 | 0.398 +/- 0.038 | -0.006 +/- 0.184 | 0.324 +/- 0.047 | 4.9 +/- 0.660 | 2.58 +/- 0.320 | 11.90 +/- 1.24 | 1.21 +/- 0.173 | 1.31 +/- 0.104 |
| 64 | 0.599 +/- 0.033 | 0.5 +/- 0.517 | 0.384 +/- 0.033 | 13.9 +/- 0.144 | 1.67 +/- 0.195 | 0.0 +/- 0.0 | 4.58 +/- 0.50 | 1.31 +/- 0.085 |

| Scenario B Arrival Time MOEs | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Run | Ability to Meet Windows (%) | Batch Mean Arrival Time | % of time early | Mean Number Early | Mean Time Early (hrs) | Mean Number Late | Mean Time Late (hrs) | Mean Delay (hrs) |
| Scenario B, Heuristic Block 2 | | | | | | | | |
| 17 | 0.608 +/- 0.021 | 0.516 +/- 0.059 | 0.374 +/- 0.021 | 13.22 +/- 0.232 | 1.43 +/- 0.138 | 0.100 +/- 0.086 | 0.204 +/- 0.038 | 1.47 +/- 0.114 |
| 18 | 0.603 +/- 0.022 | 0.53 +/- 0.098 | 0.359 +/- 0.022 | 11.66 +/- 0.695 | 1.836 +/- 0.154 | 1.34 +/- 0.3878 | 1.42 +/- 0.354 | 1.45 +/- 0.130 |
| 19 | 0.621 +/- 0.022 | 0.452 +/- 0.077 | 0.331 +/- 0.022 | 10.04 +/- 0.816 | 1.80 +/- 0.169 | 1.68 +/- 0.450 | 1.405 +/- 0.331 | 1.45 +/- 0.130 |
| 20 | 0.404 +/- 0.025 | -0.075 +/- 0.088 | 0.265 +/- 0.030 | 3.30 +/- 0.478 | 2.89 +/- 0.291 | 12.2 +/- 0.969 | 1.106 +/- 0.089 | 1.45 +/- 0.130 |
| 21 | 0.416 +/- 0.025 | -0.05 +/- 0.101 | 0.266 +/- 0.030 | 3.48 +/- 0.474 | 2.82 +/- 0.286 | 11.82 +/- 1.002 | 1.099 +/- 0.091 | 1.45 +/- 0.130 |
| 22 | 0.609 +/- 0.021 | 0.503 +/- 0.063 | 0.370 +/- 0.022 | 12.9 +/- 0.265 | 1.43 +/- 0.141 | 0.26 +/- 0.138 | 0.186 +/- 0.034 | 1.47 +/- 0.114 |
| 23 | 0.335 +/- 0.024 | 0.024 +/- 0.068 | 0.285 +/- 0.033 | 2.86 +/- 0.099 | 2.92 +/- 0.298 | 14.4 +/- 0.363 | 0.688 +/- 0.037 | 1.475 +/- 0.114 |
| 24 | 0.500 +/- 0.025 | 0.17 +/- 0.078 | 0.216 +/- 0.026 | 3.00 +/- 0.0 | 3.054 +/- 0.299 | 9.56 +/- 0.288 | 0.696 +/- 0.041 | 1.47 +/- 0.114 |
| Scenario B, Heuristic Block 4 | | | | | | | | |
| 49 | 0.510 +/- 0.029 | -0.059 +/- 0.058 | 0.081 +/- 0.021 | 0.0 +/- 0.0 | 4.75 +/- 0.172 | 9.34 +/- 0.273 | 0.591 +/- 0.029 | 1.40 +/- 0.097 |
| 50 | 0.415 +/- 0.026 | -0.049 +/- 0.105 | 0.269 +/- 0.032 | 3.64 +/- 0.457 | 2.70 +/- 0.258 | 10.0 +/- 0.623 | 1.20 +/- 0.108 | 1.38 +/- 0.078 |
| 51 | 0.546 +/- 0.024 | -0.153 +/- 0.103 | 0.354 +/- 0.022 | 2.0 +/- 0.512 | 0.978 +/- 0.154 | 9.54 +/- 0.287 | 1.1 +/- 0.110 | 1.40 +/- 0.097 |
| 52 | 0.696 +/- 0.022 | 0.301 +/- 0.087 | 0.304 +/- 0.022 | 8.54 +/- 0.264 | 0.990 +/- 0.142 | 0.0 +/- 0.0 | 0.0 +/- 0.0 | 1.40 +/- 0.097 |
| 53 | 0.366 +/- 0.027 | -0.344 +/- 0.082 | 0.209 +/- 0.033 | 1.38 +/- 0.418 | 2.49 +/- 0.374 | 12.14 +/- 0.940 | 1.08 +/- 0.094 | 1.38 +/- 0.115 |
| 54 | 0.621 +/- 0.022 | 0.453 +/- 0.077 | 0.331 +/- 0.022 | 10.04 +/- 0.816 | 1.803 +/- 0.169 | 1.68 +/- 0.450 | 1.404 +/- 0.331 | 1.45 +/- 0.130 |
| 55 | 0.682 +/- 0.022 | 0.310 +/- 0.109 | 0.318 +/- 0.022 | 9.16 +/- 0.218 | 0.977 +/- 0.134 | 0.0 +/- 0.0 | 0.161 +/- 0.0 | 1.40 +/- 0.097 |
| 56 | 0.332 +/- 0.027 | -0.226 +/- 0.065 | 0.119 +/- 0.030 | 0.0 +/- 0.0 | 4.54 +/- 0.172 | 13.42 +/- 0.363 | 0.674 +/- 0.033 | 1.40 +/- 0.097 |
| Scenario B, Exact Method | | | | | | | | |
| 9 | 0.633 +/- 0.021 | 0.483 +/- 0.044 | 0.366 +/- 0.021 | 13.42 +/- 0.304 | 1.32 +/- 0.091 | 0.0 +/- 0.0 | 0.113 +/- 0.276 | 0.886 +/- 0.039 |
| 10 | 0.606 +/- 0.022 | 0.455 +/- 0.072 | 0.363 +/- 0.022 | 12.22 +/- 0.777 | 1.46 +/- 0.101 | 1.08 +/- 0.380 | 1.049 +/- 0.177 | 0.882 +/- 0.048 |
| 11 | 0.424 +/- 0.025 | -0.114 +/- 0.069 | 0.297 +/- 0.029 | 4.46 +/- 0.603 | 1.404 +/- 0.174 | 11.1 +/- 0.903 | 0.919 +/- 0.063 | 0.882 +/- 0.048 |
| 12 | 0.629 +/- 0.021 | 0.49 +/- 0.099 | 0.371 +/- 0.021 | 13.7 +/- 0.265 | 1.328 +/- 0.090 | 0.0 +/- 0.0 | 0.188 +/- 0.0 | 0.886 +/- 0.039 |
| 13 | 0.427 +/- 0.025 | -0.135 +/- 0.051 | 0.285 +/- 0.029 | 4.12 +/- 0.609 | 1.46 +/- 0.179 | 11.16 +/- 0.912 | 0.950 +/- 0.064 | 0.882 +/- 0.048 |
| 14 | 0.374 +/- 0.024 | -0.129 +/- 0.061 | 0.290 +/- 0.032 | 3.44 +/- 0.183 | 1.36 +/- 0.174 | 13.04 +/- 0.257 | 0.705 +/- 0.031 | 0.886 +/- 0.039 |

| Scenario C Arrival Time MOEs | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Run | Ability to Meet Windows (%) | Batch Mean Arrival Time | % of time early | Mean Number Early | Mean Time Early (hrs) | Mean Number Late | Mean Time Late (hrs) | Mean Delay (hrs) | |
| Scenario C, Heuristic Block 2 | | | | | | | | | |
| 33 | 0.566 +/- 0.022 | 0.728 +/- 0.048 | 0.414 +/- 0.022 | 14.3 +/- 0.914 | 1.903 +/- 0.086 | 0.72 +/- 0.444 | 1.037 +/- 0.224 | 0.871 +/- 0.047 | |
| 34 | 0.631 +/- 0.024 | 0.263 +/- 0.066 | 0.303 +/- 0.024 | 7.72 +/- 0.152 | 1.13 +/- 0.072 | 2.06 +/- 0.068 | 0.483 +/- 0.038 | 0.878 +/- 0.039 | |
| 35 | 0.506 +/- 0.024 | 0.149 +/- 0.082 | 0.365 +/- 0.026 | 8.46 +/- 0.762 | 1.18 +/- 0.071 | 5.68 +/- 0.898 | 0.947 +/- 0.088 | 0.871 +/- 0.047 | |
| 36 | 0.558 +/- 0.022 | 0.811 +/- 0.057 | 0.428 +/- 0.022 | 15.46 +/- 0.888 | 2.01 +/- 0.086 | 0.440 +/- 0.321 | 0.996 +/- 0.244 | 0.871 +/- 0.047 | |
| 37 | 0.622 +/- 0.024 | 0.168 +/- 0.033 | 0.286 +/- 0.024 | 6.70 +/- 0.165 | 1.0 +/- 0.075 | 2.94 +/- 0.210 | 0.638 +/- 0.048 | 0.878 +/- 0.039 | |
| 38 | 0.547 +/- 0.021 | 0.73 +/- 0.031 | 0.453 +/- 0.021 | 18.08 +/- 0.161 | 1.62 +/- 0.074 | 0.0 +/- 0.0 | 0.0 +/- 0.0 | 0.878 +/- 0.039 | |
| 39 | 0.549 +/- 0.021 | 0.719 +/- 0.040 | 0.451 +/- 0.021 | 17.9 +/- 0.165 | 1.60 +/- 0.074 | 0.0 +/- 0.0 | 0.0 +/- 0.0 | 0.878 +/- 0.039 | |
| 40 | 0.511 +/- 0.024 | 0.13 +/- 0.045 | 0.359 +/- 0.026 | 8.32 +/- 0.807 | 1.17 +/- 0.071 | 5.60 +/- 0.904 | 1.0 +/- 0.086 | 0.871 +/- 0.047 | |
| Scenario C, Heuristic Block 4 | | | | | | | | | |
| 65 | 0.621 +/- 0.033 | 0.489 +/- 0.081 | 0.377 +/- 0.033 | 13.55 +/- 0.415 | 1.29 +/- 0.117 | 0.0 +/- 0.0 | 0.026 +/- 0.0 | 0.691 +/- 0.037 | |
| 66 | 0.474 +/- 0.035 | -0.168 +/- 0.067 | 0.316 +/- 0.039 | 5.88 +/- 1.16 | 0.911 +/- 0.106 | 8.28 +/- 1.37 | 1.20 +/- 0.148 | 0.703 +/- 0.044 | |
| 67 | 0.561 +/- 0.034 | 0.563 +/- 0.068 | 0.410 +/- 0.034 | 14.65 +/- 1.16 | 1.59 +/- 0.121 | 1.25 +/- 0.757 | 1.27 +/- 0.365 | 0.725 +/- 0.050 | |
| 68 | 0.532 +/- 0.038 | 0.065 +/- 0.041 | 0.305 +/- 0.040 | 6.35 +/- 0.314 | 0.694 +/- 0.085 | 6.4 +/- 0.535 | 0.415 +/- 0.057 | 0.691 +/- 0.037 | |
| 69 | 0.618 +/- 0.033 | 0.489 +/- 0.052 | 0.381 +/- 0.033 | 13.8 +/- 0.244 | 1.31 +/- 0.116 | 0.0 +/- 0.0 | 0.0 +/- 0.0 | 0.691 +/- 0.037 | |
| 70 | 0.490 +/- 0.039 | -0.123 +/- 0.105 | 0.308 +/- 0.042 | 5.85 +/- 1.26 | 0.938 +/- 0.121 | 7.75 +/- 1.31 | 1.11 +/- 0.160 | 0.725 +/- 0.050 | |
| 71 | 0.567 +/- 0.034 | 0.475 +/- 0.103 | 0.392 +/- 0.035 | 13.15 +/- 1.34 | 1.51 +/- 0.122 | 1.51 +/- 0.122 | 1.80 +/- 0.919 | 1.17 +/- 0.307 | |
| 72 | 0.499 +/- 0.039 | 0.008 +/- 0.032 | 0.296 +/- 0.042 | 5.35 +/- 0.275 | 0.675 +/- 0.089 | 7.85 +/- 0.380 | 0.465 +/- 0.055 | 0.691 +/- 0.037 | |
| Scenario C, Exact Method | | | | | | | | | |
| 1 | 0.572 +/- 0.025 | 0.464 +/- 0.049 | 0.381 +/- 0.026 | 9.32 +/- 0.133 | 1.48 +/- 0.087 | 1.22 +/- 0.119 | 0.744 +/- 0.118 | 0.586 +/- 0.027 | |
| 2 | 0.541 +/- 0.026 | 0.408 +/- 0.045 | 0.373 +/- 0.027 | 8.02 +/- 0.543 | 1.73 +/- 0.113 | 2.86 +/- 0.441 | 1.08 +/- 0.149 | 0.577 +/- 0.032 | |
| 3 | 0.569 +/- 0.025 | 0.504 +/- 0.058 | 0.386 +/- 0.026 | 9.6 +/- 0.141 | 1.57 +/- 0.087 | 1.16 +/- 0.105 | 0.753 +/- 0.120 | 0.753 +/- 0.120 | |
| 4 | 0.539 +/- 0.025 | 0.513 +/- 0.059 | 0.390 +/- 0.026 | 8.96 +/- 0.545 | 1.84 +/- 0.112 | 2.38 +/- 0.371 | 1.07 +/- 0.150 | 0.577 +/- 0.032 | |
| 5 | 0.422 +/- 0.029 | -0.259 +/- 0.057 | 0.256 +/- 0.034 | 2.64 +/- 0.169 | 0.963 +/- 0.152 | 8.46 +/- 0.154 | 0.978 +/- 0.047 | 0.586 +/- 0.027 | |
| 6 | 0.405 +/- 0.028 | -0.281 +/- 0.120 | 0.324 +/- 0.034 | 3.64 +/- 0.559 | 1.25 +/- 0.158 | 8.44 +/- 0.608 | 1.30 +/- 0.097 | 0.577 +/- 0.032 | |
| 7 | 0.569 +/- 0.025 | 0.454 +/- 0.044 | 0.379 +/- 0.026 | 9.08 +/- 0.113 | 1.48 +/- 0.087 | 1.42 +/- 0.142 | 0.711 +/- 0.115 | 0.586 +/- 0.027 | |
| 8 | 0.390 +/- 0.028 | -0.351 +/- 0.074 | 0.319 +/- 0.035 | 3.3 +/- 0.554 | 1.24 +/- 0.164 | 8.92 +/- 0.599 | 1.35 +/- 0.095 | 0.577 +/- 0.032 | |

THIS PAGE INTENTIONALLY LEFT BLANK

## LIST OF REFERENCES


Adams, Major Mark A., USMC, 1st BSSG XO, E-mail correspondence between Major Adams and the author, June 12, 2001.

Allen, Scott A., "USMC Tactical Motor Transport Lift Requirements Model," M.S. Thesis in Management, Naval Postgraduate School, Monterey, CA 93943, March 1995.

Armstrong, Major Neita, USMC, 1st FSSG, "LOG 2000 Combat Service Support Estimator EXCEL Spreadsheet," May 24, 2000.

ATCL-T, Directorate of Combat Developments for Transportation, United States Army, TC-AIMS II White Paper, An Operational Guide Describing How the U.S. Army Will Use the Joint System, U.S. Army Combined Arms Support Command, October 30, 1999.

Beddoes, Mark W., "Logistical Implications of Operational Maneuver From The Sea," M.S. Thesis in Operations Research, Naval Postgraduate School, Monterey, CA 93943, March 1997.

Box, George E. P., Hunter, William G. and Hunter, J. Stuart, Statistics for Experimenters, An Introduction to Design, Data Analysis, and Model Building, John Wiley & Sons, Inc., 1978.

Bramel, J., and Simchi-Levi D., The Logic of Logistics: theory, algorithms, and applications for logistics management, Springer-Verlag, 1997.

Brinkley, C. Mark, "Punching Up 911, A Brand-New Vision for Tomorrow's Marine Corps," Marine Corps Times, pp. 14-16, December 4, 2000.

Brooke, A., Kendrick, D., Meeraus, A., and Raman, R., GAMS, A Users Guide, GAMS Development Corporation, 1998.

Chapman, Art, E-mail correspondence between Mr. Chapman and Professor Kevin R. Gue, Naval Postgraduate School, with carbon copy to the author, California Polytechnic Institute, October 05, 2000.

Edwards, John E., Combat Service Support Guide 2d ed., Harrisburg, PA: Stackpole Books, 1993.

France, S. A., CPLEX 6.5 Reference Manual, ILOG, ILOG, 1999.

Frey, Christopher M., "An Evaluation of Sea-Based Sustainment of Forces," M.S. Thesis in Operations Research, Naval Postgraduate School, Monterey, CA 93943, September 2000.

Gannon, Major James M., USMC, 1st FSSG G-3 CurOps, E-mail correspondence between Major Gannon and the author, October 18, 2000.

Gannon, Major James M., USMC, 1st FSSG G-3 CurOps, E-mail correspondence between Major Gannon and the author, November 03, 2000.

Gannon, Major James M., USMC, 1st FSSG G-3 CurOps, Quad FSSG CSSOC SOP (Working Paper), February 03, 2001.

Golden, B. L., and Assad, A. A., Vehicle Routing: Methods and Studies, North Holland, Amsterdam, 1998.

Grelson, Colonel Jeff D., USMC, 1st BSSG Commanding Officer, "Logistics Operations Command and Control Capability (LOCCC) (Working Paper)," November 2000.

Gue, Kevin R., "A Dynamic Distribution Model for Combat Logistics," Department of Systems Management, Naval Postgraduate School, Monterey, CA 93943, February 2000.

Hagan, Robert M., "Modeling Sea-based Sustainment of Marine Expeditionary Unit Special Operations Capable)(MEU(SOC)) Operations Ashore," M.S. Thesis in Operations Research, Naval Postgraduate School, Monterey, CA 93943, September, 1998.

Ihaka, Ross, and Gentleman, Robert, "R: A Language for Data Analysis and Graphics," Journal of Computational and Graphical Statistics 5.3, pp. 299 – 314, 1996.

Jackson, Jack, Konig [Computer software], www.trac.nps.navy.mil/jacksonl/konig., 1999.

Joint Pub 4-01.3, Joint Tactics, Techniques and Procedures for Movement Control, http://www.dtic.mil/doctrine/jel/logistics.htm, June 1996.

Jordan, Jeffrey L., Water Resource Economics, University of Georgia, http://www.griffin.peachnet.edu/agecon/home.htm, March 2001.

Krulak, General Charles C., 31st Marine Corps Commandant, Planning Guidance in White Paper, "Operational Maneuver From the Sea," 1997.

Laporte, G., "The Vehicle Routing Problem: An Overview of Exact and Approximate Algorithms," European Journal of Operational Research 59, pp. 345, 1992.

Law, Averill M., and Kelton, W. David, Simulation Modeling and Analysis (third edition), McGraw-Hill, 2000.

Lewler, E. L., et al. The Traveling Salesman Problem. Wiley-Interscience, 1985.

Marine Air-Ground Task Force (MAGTF) Staff Training Program (MSTP), Quantico, Virginia, Marine Corps Combat Development Command, December 1999.

Marine Corps Technical Characteristics Manual, TM 11240-15/4B, Quantico, Virginia, Marine Corps Systems Command, August 1994.

Marine Corps Warfighting Publication 4-1, Logistics Operations, Quantico, Virginia, Marine Corps Combat Development Command, April 1999.

Marine Corps Warfighting Publication 4-11, Tactical Level Logistics, Quantico, Virginia, Marine Corps Combat Development Command, June 2000.

Marine Corps Warfighting Publication 4-11.3, Transportation Operations (Coordinating Draft), Quantico, Virginia, Marine Corps Combat Development Command, October 1999.

McLaughlin, Brett, Java and XML. O'Reilly and Associates, Inc., 2000.

Nemhauser, G. and Wolsey, L., "Integer and Combinatorial Optimization," John Wiley and Sons 1988.

O'Donovan, John A., "Combat Service Support During Desert Shield and Desert and Desert Storm: From Kibrit to Kuwait," Marine Corps Gazette, pp. 26-31, October 1991.

Parker, Captain W. P., 1st BSSG Assistant Operations Officer, "Exercise Desert Knight/ Steel Knight 2001, Commanding Officer Confirmation Brief," November 16, 2000.

Reitter, Norman L., "A Decision Support System for Sea-Based Sustainment Operations," M.S. Thesis in Operations Research, Naval Postgraduate School, Monterey, CA 93943, September 1999.

Savelsberg, M.W.P., "Local Search in Routing Problems with Time Windows," Annals of Operations Research 4, pp. 285, 1985.

Solomon, M.M., "Algorithms for the Vehicle Routing and Scheduling Problems with Time Window Constraints," Operations Research 35, pp. 254, 1987.

Stork, Kirk, "Sensors in Object Oriented Discrete Event Simulation," M.S. Thesis in Operations Research, Naval Postgraduate School, Monterey, CA 93943, 1996.

THIS PAGE INTENTIONALLY LEFT BLANK

## INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Fort Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California

3. Marine Corps Representative
   Naval Postgraduate School
   Monterey, California

4. Director, Training and Education, MCCDC, Code C46
   Quantico, Virginia

5. Director, Marine Corps Research Center, MCCDC, Code C40RC
   Quantico, Virginia

6. Marine Corps Tactical Systems Support Activity (Attn: Operations Officer)
   Camp Pendleton, California

7. Director, Studies and Analysis Division, MCCDC, Code C45
   Quantico, Virginia

8. Director, Marine Corps Systems Command, MCCDC, Code C4IIS
   Quantico, Virginia

9. Brigade Service Support Group One (Attn: Commanding Officer)
   Colonel Jeff D. Grelson

10. 1st Force Service Support Group (Attn: Lieutenant Colonel Gannon)
Camp Pendleton, California

11. Chairman, Department of Operations Research, Code OR/Er
Naval Postgraduate School
Monterey, California

12. Professor Arnold H. Buss, Code OR/Bu
Naval Postgraduate School
Operations Research Department
Monterey, California

13. Professor Gordon H. Bradley, Code OR/Bz
Naval Postgraduate School
Operation Research Department
Monterey, California

14. Professor Javier Salmeron, Code OR/Sa
Naval Postgraduate School
Operations Research Department
Monterey, California

15. Captain Thomas A. Lenhardt